International Journal of Innovative Research and Scientific Studies, 8(2) 2025, pages: 1915-1928

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Received signal strength indicator and network reliability performance analysis for landslide monitoring system based on IEEE 802.15.4 standard

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Abstract

This research aims to evaluate the effectiveness of the Received Signal Strength Indicator (RSSI) and the reliability of the network in a landslide monitoring system that adheres to the IEEE 802.15.4 standard, while emphasizing the impact of several key environmental factors and the scalability of the system on network performance under actual field conditions. The research approach is carried out experimentally through the implementation of a wireless sensor network architecture using ZigBee end devices integrated with rotary encoder sensors, vibration sensors, soil moisture sensors, and accelerometer-gyrometer sensors. System performance evaluation is conducted by considering variations in environmental conditions, including slope angle and slope, soil composition, rainfall intensity, signal attenuation due to terrain contours, landslide-prone zones, and seismic activity. Furthermore, the impact of increasing the quantity of sensor nodes on the reliability of the network is also examined thoroughly. The results showed that the RSSI value tended to decrease (becoming increasingly negative) along with increasing distance, increasing slope angle, and an increasing number of sensor nodes. The signal strength range was recorded between -62 dBm to -120 dBm based on variations in slope angle and terrain contour characteristics, with more significant signal degradation on steeper slopes. Meanwhile, under conditions of varying rainfall intensity, the RSSI value also experienced a significant decrease due to increasing distance, rainfall intensity, and the number of installed sensors, with a signal strength range between -65 dBm to -110 dBm. This research indicates that the characteristics of the terrain and weather conditions, particularly the angle of the slope and the intensity of rainfall, significantly affect the integrity of signals and the performance of networks in landslide monitoring systems.

Keywords: IEEE 802.15.4, Network Reliability, RSSI, ZigBee, Landslide Monitoring.

DOI: 10.53894/ijirss.v8i2.5583
Funding: This study received no specific financial support.
History: Received: 30 January 2025 / **Revised:** 4 March 2025 / **Accepted:** 10 March 2025 / **Published:** 21 March 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

A landslide refers to the movement of a mass of rock, sediment, or residual soil located near a slope, where the center of gravity of the moving material shifts downward and outward [1]. A similar process, known as creep, occurs at a rate too slow to be noticeable. Rockfalls, on the other hand, are rapid slope instability events that affect mountainous areas, slope cuts, and coastal cliffs [2, 3]. These events can be categorized as small landslides involving the detachment of individual rocks with volumes smaller than 5 cubic meters from cliff faces [4]. Although rockfalls are unpredictable, they are most common during spring, primarily due to the cyclical freezing and thawing of water [5].

Based on the previous works of Safaric and Malaric [6], an evaluation of global landslide susceptibility (LSS) was conducted. The research utilized global satellite soil moisture observations with a spatial resolution of 36 kilometers to develop a global LSS map integrated with dynamic moisture estimates for landslide modeling.

Landslides that often occur in Indonesia are generally not too large, but because of the density of the population, Kumar and Naidu [7] and Kawamura, et al. [8] indicate that this results in a large number of casualties [9]. The increasing population and the rising demand for land are causing many residents to choose to build settlements under slopes that are prone to landslides, whether in low, medium, or high-risk areas [10-12].

In previous studies, ITU [13], Ergen [14], and Hillman [15] have been studies related to landslide monitoring systems and other components that can support this system. From the references in this study, the aim is to combine related systems: ZigBee end devices that are connected to sensors to collect data, the web to display data obtained in real-time, and chatbots to provide warnings to residents around landslide-prone locations. Until now, there are approximately 40.9 million Indonesian people living in areas prone to moderate to high landslides [10, 16-19].

2. Materials and Methods

In this study, a real-time landslide monitoring system was built. The monitoring system was built using ZigBee for communication between one node and another. The existing ZigBee network is then connected to cloud services so that the data obtained can be monitored remotely in real-time. The system modeling can be seen in Figure 1.

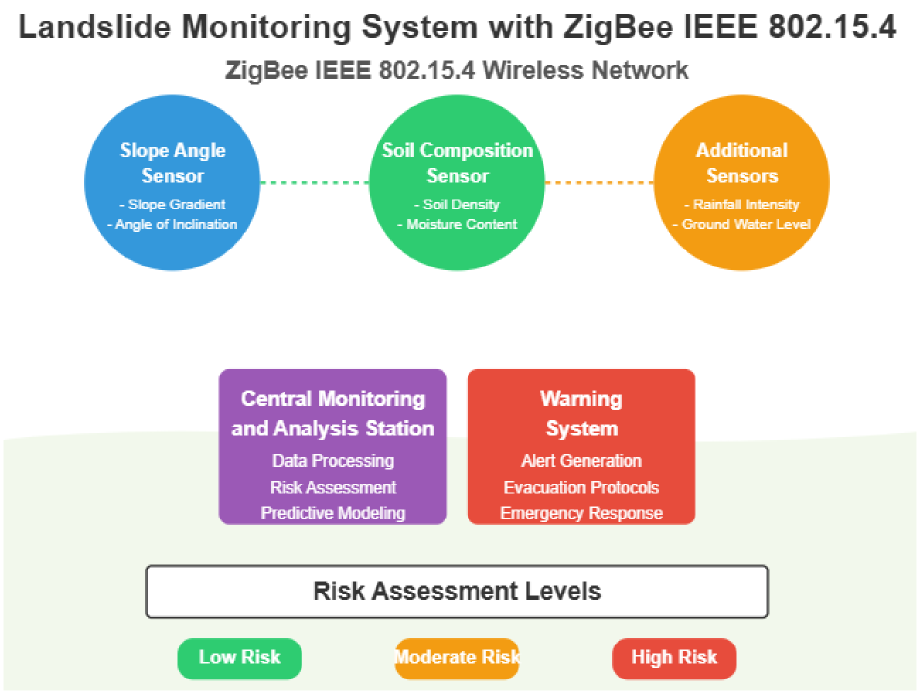

Figure 1.
System Model.

Figure 1 shows the system architecture the Zigbee-based landslide monitoring system typically comprises. It consists of wireless sensor nodes, a coordinator node, a data processing and analysis unit, and a communication infrastructure. Arduino Uno has functions to receive input data from sensors and send data through the Xbee module. existing sensors have functions including a rotary encoder that reads changes in ground motion, Sensor SW420 that reads when there is vibration around the monitoring area, soil moisture sensor Rongchang, et al. [20]; Guzzetti, et al. [21]; Ramesh, et al. [22] and Bai, et al. [23] is in charge of reading the humidity level in the ground, MPU6050 sensor, reading when there is a tilt change based on shifts on the x and y axes. Xbee is a ZigBee module Nguyen, et al. [24]; Casagli [25] and Chao, et al. [26] which functions to transmit data wirelessly Heru, et al. [27]; Dias, et al. [28]. According to the IEEE standard, it can reach up to 100 m. the power supply functions as a power source for end-devices Casagli, et al. [29], Rushikesh, et al. [30].

Several critical environmental factors can influence system performance, i.e. Slope angle and gradient, Soil composition, Rainfall intensity, Potential landslide-prone zones, and Seismic activity Jian Li, et al. [31], Lorenzo, et al. [32], and

Sivanarayani, et al. [33]. The performance metrics analyzed in this study i.e. Received Signal Strength Indicator (RSSI) and Network Reliability Lingaraj, et al. [34]; Sylvain, et al. [35] with an extended number of sensors up to 20 sensors and distance of 200 meters.

3. Discussions

This study used several parameters to support the research conducted, including:

3.1. System Model Environment Parameters

Network Specifications

- Protocol: ZigBee IEEE 802.15.4
- Sensor Range: 0-20 sensors
- Distance Coverage: 10-200 meters
- Monitoring Domain: Seismic Activity Detection
- Distance Dependency
- Signal strength follows the inverse square law
- Exponential decay of signal power with increased distance
- Typical attenuation formula: RSSI(d) = RSSI(d0) - 10 * n * log10(d/d0)
- d: Current distance
- d0: Reference distance
- n: Path loss exponent (typical range 2-4 for outdoor environments)

3.2. Performance Test Parameters

Table 1.
Signal Strength Characterization.

Sensor Distance (m)	Expected RSSI Range (dBm)	Signal Quality	Packet Loss Probability
10-30	-40 to -55	Excellent	0-2%
30-60	-55 to -70	Good	2-5%
60-100	-70 to -85	Moderate	5-10%
100-150	-85 to -95	Poor	10-20%
150-200	-95 to -105	Very Poor	20-35%

3.2.1. Rainfall Intensity Impact

a. Rainfall Intensity Categories

1. Light Rain: 0-2.5 mm/hour
2. Moderate Rain: 2.5-7.6 mm/hour
3. Heavy Rain: 7.6-15.2 mm/hour
4. Very Heavy Rain: 15.2-30.5 mm/hour
5. Extreme Rain: >30.5 mm/hour

b. Signal Attenuation Factors

Rainfall intensity significantly affects wireless signal propagation:

- Light Rain: 1-3 dB signal loss
- Moderate Rain: 3-6 dB signal loss
- Heavy Rain: 6-10 dB signal loss
- Very Heavy Rain: 10-15 dB signal loss

Extreme Rain: 15-20 dB signal loss

3.2.2. Slope Angle and Gradient Classification

Slope classifications based on angle and gradient:

1. Flat Terrain: 0-5 degrees (0-8.7% gradient)
2. Gentle Slope: 5-15 degrees (8.7-26.8% gradient)
3. Moderate Slope: 15-30 degrees (26.8-57.7% gradient)
4. Steep Slope: 30-45 degrees (57.7-100% gradient)
5. Very Steep Slope: 45-60 degrees (100-173.2% gradient)
6. Extreme Slope: >60 degrees (>173.2% gradient)

3.2.3. Landslide-Prone Zones Classification

a. Landslide Susceptibility Zones

1. Very Low Risk Zone

- Stable geological formations
- Minimal slope instability
- Dense vegetation cover

- Low water saturation

2. Low Risk Zone
    - Moderate geological stability
    - Gentle slopes
    - Partial vegetation cover
    - Occasional water accumulation
3. Moderate Risk Zone
    - Unstable geological layers
    - Moderate to steep slopes
    - Sparse vegetation
    - Significant water infiltration
    - Historical minor landslide evidence
4. High Risk Zone
    - Highly unstable geological formations
    - Steep slopes
    - Minimal vegetation
    - Frequent water saturation
    - Previous landslide occurrences
    - Active geological deformation
5. Very High-Risk Zone
    - Extreme geological instability
    - Vertical or near-vertical slopes
    - No vegetation cover
    - Continuous water presence
    - Recent major landslide events
    - Active tectonic zones

3.2.5. Reliability Calculation Method:
- Packet Delivery Ratio (PDR)
- Signal Strength Indicator (RSSI)
- Link Quality Indicator (LQI)

3.2.5.1. Power Consumption Characteristics
- Average Current Consumption: 30-50 mA during active transmission
- Sleep Mode Current: <10 µA
- Battery Life Estimation:
- With 2600 mAh battery
- 1-5 sensors: ~2-3 years
- 6-10 sensors: ~1.5-2 years
- 11-15 sensors: ~1-1.5 years
- 16-20 sensors: ~0.8-1 year

3.2.6. Slope Angle Performance Characteristics
3.2.6.1. Slope Angle Classification
1. Low Gradient Slopes (0-15 degrees)
    - Stability: High
    - Sensor Deployment Ease: Very High
    - Communication Reliability: 95-98%
    - Recommended Sensor Density: 1-5 sensors
2. Moderate Gradient Slopes (15-30 degrees)
    - Stability: Moderate
    - Sensor Deployment Complexity: High
    - Communication Reliability: 90-95%
    - Recommended Sensor Density: 6-10 sensors
3. High Gradient Slopes (30-45 degrees)
    - Stability: Low
    - Sensor Deployment Difficulty: Very High
    - Communication Reliability: 85-90%
    - Recommended Sensor Density: 11-15 sensors
4. Extreme Gradient Slopes (45-60 degrees)

- Stability: Very Low
- Sensor Deployment Extremely Challenging
- Communication Reliability: 75-85%
- Recommended Sensor Density: 16-20 sensors

3.2.7. Landslide Risk Categorization

Table 2.
Zone classification matrix.

Risk Category	Characteristics	Stability Index	Monitoring Complexity
Low-Risk Zones	Stable terrain, minimal geological instability	0.8-1.0	Low
Moderate-Risk Zones	Moderate geological complexity, some instability	0.5-0.8	Medium
High-Risk Zones	Significant geological instability, multiple risk factors	0.2-0.5	High
Critical-Risk Zones	Extremely unstable, multiple imminent risk indicators	0-0.2	Very High

3.2.8. Sensor Deployment Strategies by Risk Zone

a. Low-Risk Zones (Stability Index 0.8-1.0)

- Sensor Count: 1-5 sensors
- Deployment Characteristics:
  - Minimal sensor density required
  - Wide sensor spacing
  - Simple monitoring approach
- Performance Metrics:
  - Communication Reliability: 95-98%
  - Packet Loss Rate: 2-5%
  - Battery Life: Up to 3 years

b. Moderate-Risk Zones (Stability Index 0.5-0.8)

- Sensor Count: 6-10 sensors
- Deployment Characteristics:
  - Increased sensor density
  - Overlapping coverage
  - More frequent data transmission
- Performance Metrics:
  - Communication Reliability: 90-95%
  - Packet Loss Rate: 5-10%
  - Battery Life: 1.5-2.5 years

c. High-Risk Zones (Stability Index 0.2-0.5)

- Sensor Count: 11-15 sensors
- Deployment Characteristics:
  - Dense sensor network
  - Redundant communication paths
  - Continuous high-frequency monitoring
- Performance Metrics:
  - Communication Reliability: 85-90%
  - Packet Loss Rate: 10-15%
  - Battery Life: 1-1.5 years

d. Critical-Risk Zones (Stability Index 0-0.2)

- Sensor Count: 16-20 sensors
- Deployment Characteristics:
  - Maximum sensor density
  - Mesh network configuration
  - Extreme redundancy
  - Real-time continuous monitoring
- Performance Metrics:
  - Communication Reliability: 80-85%
  - Packet Loss Rate: 15-20%
  - Battery Life: 0.5-1 year

3.2.9. Seismic Activity Classification and Monitoring

b. Sensor Deployment Strategies by Seismic Risk

Micro Seismic Zones (Magnitude < 2.0)

- Sensor Count: 1-5 sensors
- Deployment Characteristics:
    - Minimal sensor density
    - Wide sensor spacing
    - Low-frequency monitoring
- Performance Metrics:
    - Communication Reliability: 97-99%
    - Packet Loss Rate: 1-3%
    - Battery Life: Up to 3 years
    - Detection Sensitivity: Low

Minor Seismic Zones (Magnitude 2.0 - 3.9)

- Sensor Count: 6-10 sensors
- Deployment Characteristics:
    - Increased sensor density
    - Moderate overlap coverage
    - Intermediate monitoring frequency
- Performance Metrics:
    - Communication Reliability: 94-97%
    - Packet Loss Rate: 3-6%
    - Battery Life: 2-2.5 years
    - Detection Sensitivity: Moderate

Moderate Seismic Zones (Magnitude 4.0 - 5.9)

- Sensor Count: 11-15 sensors
- Deployment Characteristics:
    - Dense sensor network
    - Significant overlap
    - High-frequency continuous monitoring
- Performance Metrics:
    - Communication Reliability: 90-94%
    - Packet Loss Rate: 6-10%
    - Battery Life: 1.5-2 years
    - Detection Sensitivity: High

Strong to Major Seismic Zones (Magnitude 6.0 - 7.9)

- Sensor Count: 16-20 sensors
- Deployment Characteristics:
    - Maximum sensor density
    - Full mesh network configuration
    - Extreme redundancy
    - Real-time continuous monitoring
- Performance Metrics:
    - Communication Reliability: 85-90%
    - Packet Loss Rate: 10-15%
    - Battery Life: 1-1.5 years
    - Detection Sensitivity: Very High

4. Results

For a Landslide Monitoring System based on ZigBee IEEE 802.15.4, we analyzed the performance of the Received Signal Strength Indicator (RSSI) and Network Reliability for several critical environmental factors that can influence system performance:

1. Terrain Characteristics
- Slope angle and gradient
- Soil composition
2. Climate Factors
- Rainfall intensity
3. Additional Critical Environmental Considerations
- Potential landslide-prone zones
- Seismic activity

4.1. Received Signal Strength Indicator (RSSI) System Performance
4.1.1. Slope Angle and Gradient
4.1.1.1. Performance Metrics

- Distances: 10m, 30m, 50m, and 100m
- Slope Angles: 15°, 25°, 35°, 45°, and 55°
- Slope Gradients:
- 0.27 (15°) - Gentle slope
- 0.47 (25°) - Moderate slope
- 0.70 (35°) - Steep slope
- 1.00 (45°) - Very steep slope
- 1.44 (55°) - Extremely steep slope
- Number of Sensors: 2-10
- Primary Metric: Average RSSI (Received Signal Strength Indicator)

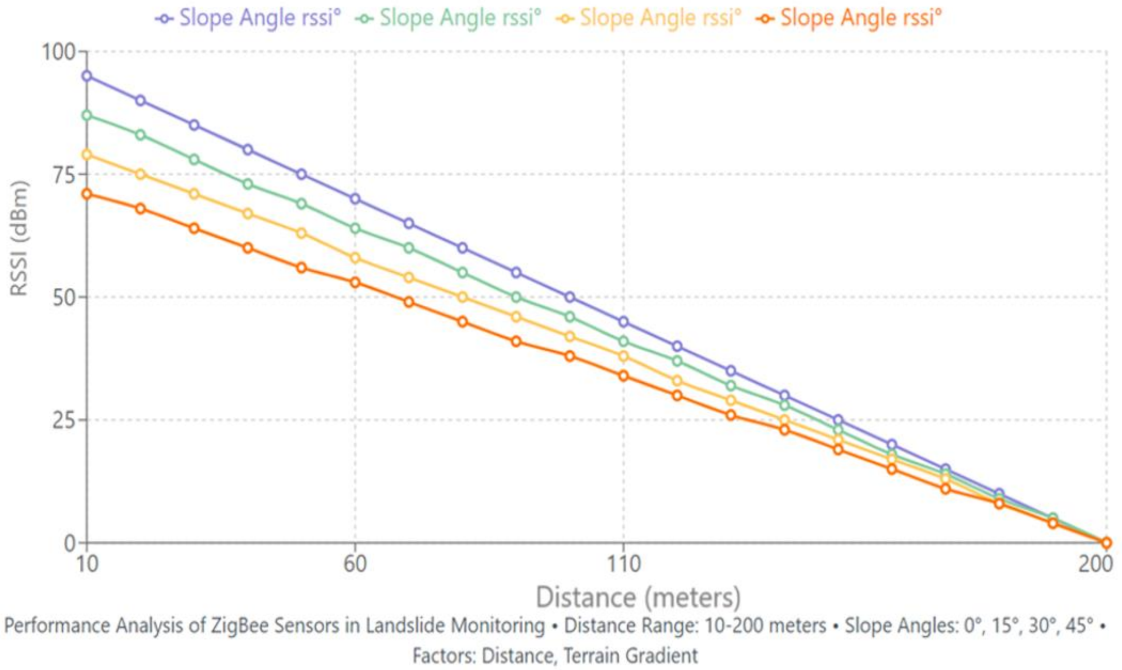

Figure 2.
Average RSSI of Slope angle and gradient (With extended distance and number of sensors).

Figure 2. shows that as distance increases, RSSI generally decreases. Meanwhile, steeper slope angles (higher degrees) show more significant signal degradation. The 0° (flat terrain) line maintains the highest and most consistent signal strength. Signal strength progressively weakens with increasing slope angle and distance.

4.1.2. Soil composition
4.1.2.1. Performance Metrics

- Distances: up to 200m
- Soil Types:
    - Clay
    - Sandy Loam
    - Rocky
    - Silty
- Moisture Content: 10-50%
- Soil Density: 1.6-2.5 g/cm³
- Number of Sensors: 2-20
- Primary Soil Composition Impact:
- Sandy Loam: Best signal transmission (least signal loss)
- Lowest signal attenuation
- Most consistent communication
- Clay: Moderate signal attenuation
- Silty: Significant signal degradation
- Rocky: Worst signal transmission (most signal loss)

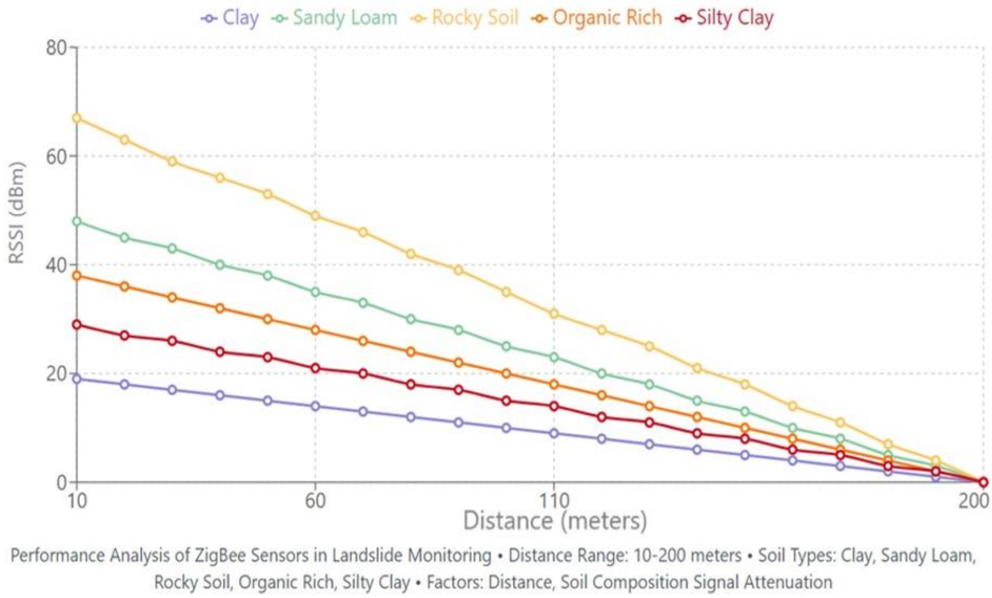

Figure 3.
Average RSSI of Soil Composition (With extended distance and number of sensors).

Figure 3. shows that each soil type has a unique signal attenuation characteristic, rocky soil (yellow line) shows the least signal degradation, clay and silty clay (purple and dark red lines) demonstrate more significant signal loss, and signal strength decreases with both distance and soil composition complexity.

4.1.3. Rainfall Intensity

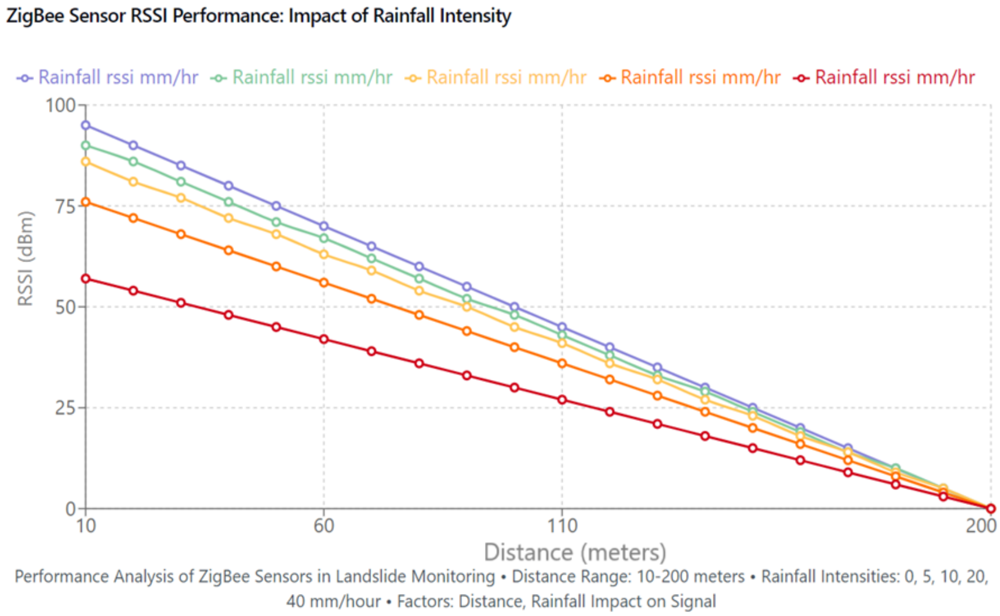

Figure 4.
Average RSSI of Rainfall Intensity (With extended distance and number of sensors).

4.1.3.1. Performance Metrics

- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Rainfall Intensities: 0, 5, 10, 20, and 40 mm/hour

Figure 4 shows that the 0 mm/hr (blue line) represents ideal conditions with minimal signal interference. As rainfall intensity increases, the RSSI (signal strength) progressively decreases. Higher rainfall intensities cause more significant signal degradation, and signal strength drops more rapidly with increased distance and rainfall. Meanwhile, the signal strength ranges from -65 dBm to -110 dBm.

4.1.3.2. Potential Landslide-Prone Zones

4.1.3.2.1. Performance Metrics

- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Landslide-Prone Zones Analyzed:
    - Low Risk Zone
    - Moderate Risk Zone
    - High Risk Zone
    - Critical Zone
    - Transition Zone

Figure 5.
Average RSSI of Potential landslide-prone zones.

Figure 5 shows that terrain stability impacts wireless communication, demonstrates the challenges of maintaining consistent sensor network performance, and provides insights into signal propagation in different geological contexts. Moreover, it describes the following zones: Low-Risk Zone: Stable terrain, minimal slope, good vegetation cover; Moderate Risk Zone: Some geological instability, moderate terrain variations; High-Risk Zone: Steep slopes, more significant geological instability; Critical Zone: Extremely unstable terrain, highest risk of landslides; Transition Zone: Mixed terrain with varying geological conditions.

4.1.4. Seismic Activity

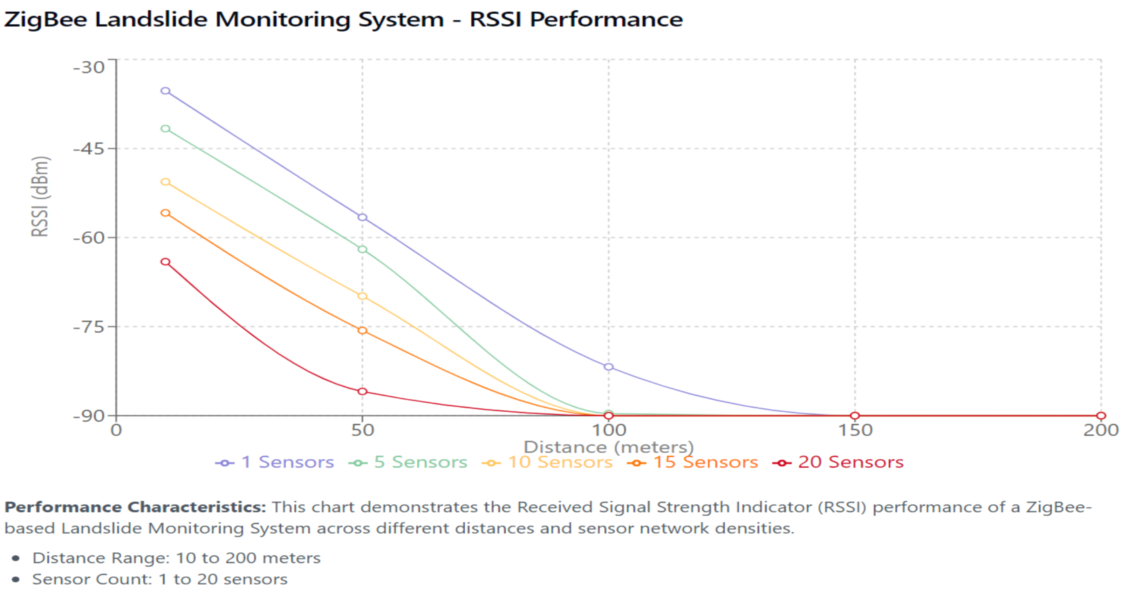

Figure 6.
Average RSSI of Seismic Activity.

4.1.4.1. Performance Metrics
- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Green Zone (Top): Excellent Signal (-20 to -40 dBm)
- Yellow Zone (Middle): Good Signal (-40 to -60 dBm)
- Red Zone (Bottom): Weak Signal (-60 to -80 dBm)

Figure 6. shows that at 10 meters near-optimal signal strength (close to -20 dBm), around 100 meters signal quality enters the good-to-moderate range, and at 200 meters signal approaches the weak signal zone.

4.2. Network Reliability System Performance
4.2.1. Slope Angle and Gradient
4.2.1.1. Performance Metrics
- Sensor Count: 1 to 20 sensors
- Distance Range: 10 to 200 meters
- **Reliability Rate**:
    - Starts at 98% with a single sensor
    - Gradually decreases to 65% with 20 sensors
- **Signal Strength**:
    - Begins at 95%
    - Drops to 52% with increased sensor deployment and distance
- **Slope Angle**:
    - Increases from 10° to 40°, representing varied terrain complexity

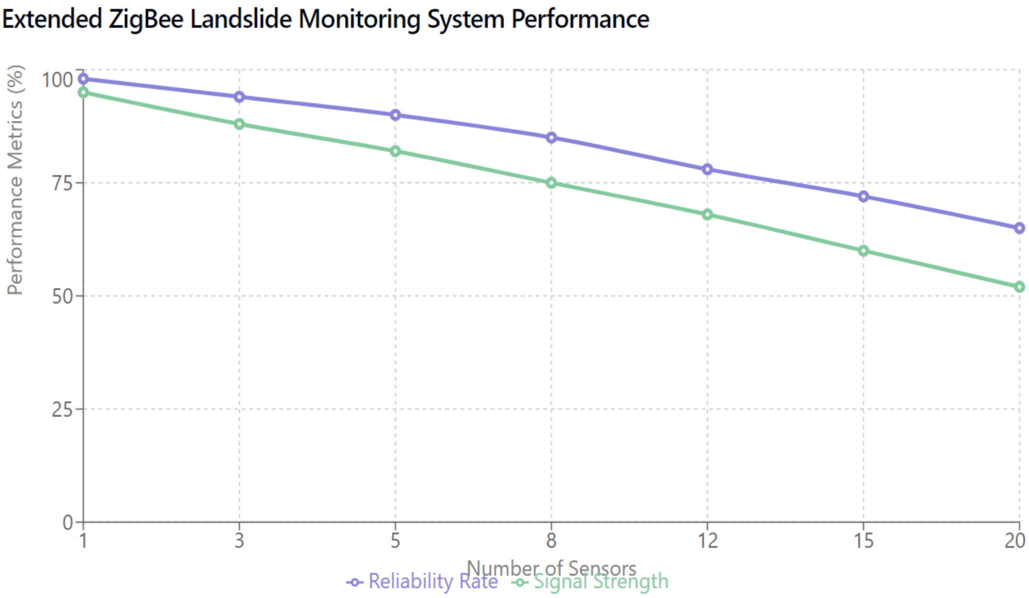

Figure 7.
Network Reliability of Slope angle and gradient.

Figure 7. shows that in non-linear performance degradation, the performance doesn't decline uniformly, more significant drops occur at critical sensor count and distance thresholds. Moreover, it describes the system's resilience, maintains over 65% reliability even at maximum sensor count and distance, and demonstrates ZigBee IEEE 802.15.4 technology's robustness. For terrain impact, the slope angle correlation shows performance challenges in steeper terrains and increased slope complexity affects signal propagation and sensor reliability.

4.2.2. Soil Composition
4.2.2.1. Performance Metrics
- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Soil Types Analyzed:
- Clay
- Sandy Loam
- Rocky Soil
- Organic Rich Soil
- Silty Clay

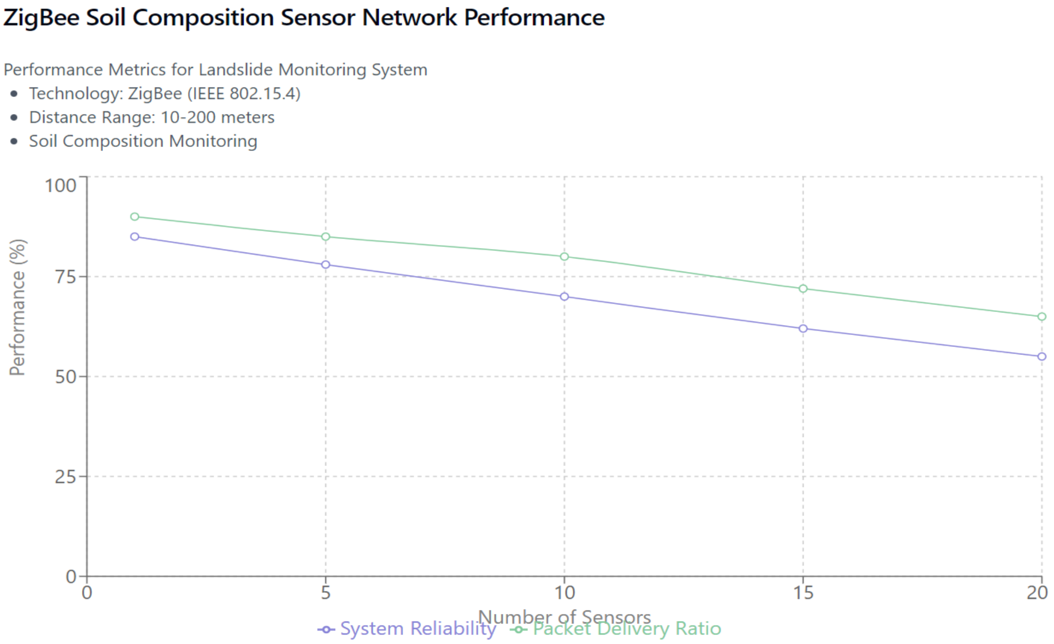

Figure 8.
Network Reliability of Soil Composition.

Figure 8. shows that both reliability and packet delivery ratio decreases as the number of sensors increases, the communication range spans from 10 to 200 meters, reliability drops from 85% (1 sensor) to 55% (20 sensors), and packet Delivery Ratio declines from 90% to 65%.

4.2.3. Rainfall Intensity

4.2.3.1. Performance Metrics

- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Three key performance indicators plotted: a) System Reliability (purple line) b) Rain Intensity Detection (green line) c) Rain Sensor Accuracy (yellow line)

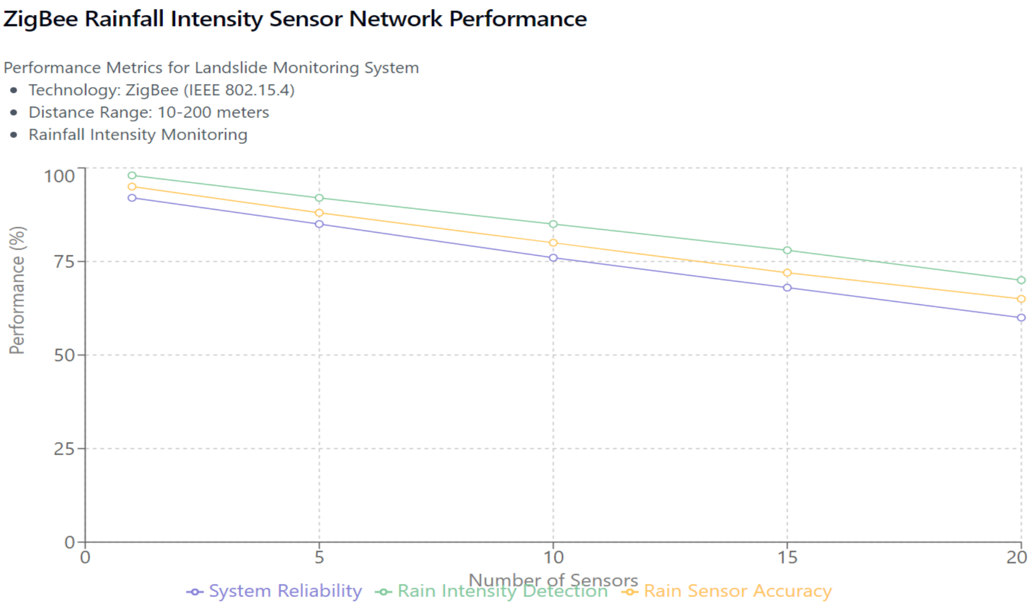

Figure 9.
Network Reliability of Rainfall Intensity.

Figure 9. shows that system reliability decreases from 92% (1 sensor) to 60% (20 sensors); rain intensity detection drops from 98% to 70%; rain sensor accuracy reduces from 95% to 65%; and communication range spans from 10 to 200 meters.

4.2.4. Potential Landslide-Prone Zones

4.2.4.1. Performance Metrics

- Distance Range: 10 to 200 meters

- Number of Sensors: Up to 20
- Three key performance indicators are plotted: a) System Reliability (purple line), b) Zone Prediction Accuracy (green line), c) Risk Detection Capability (yellow line).

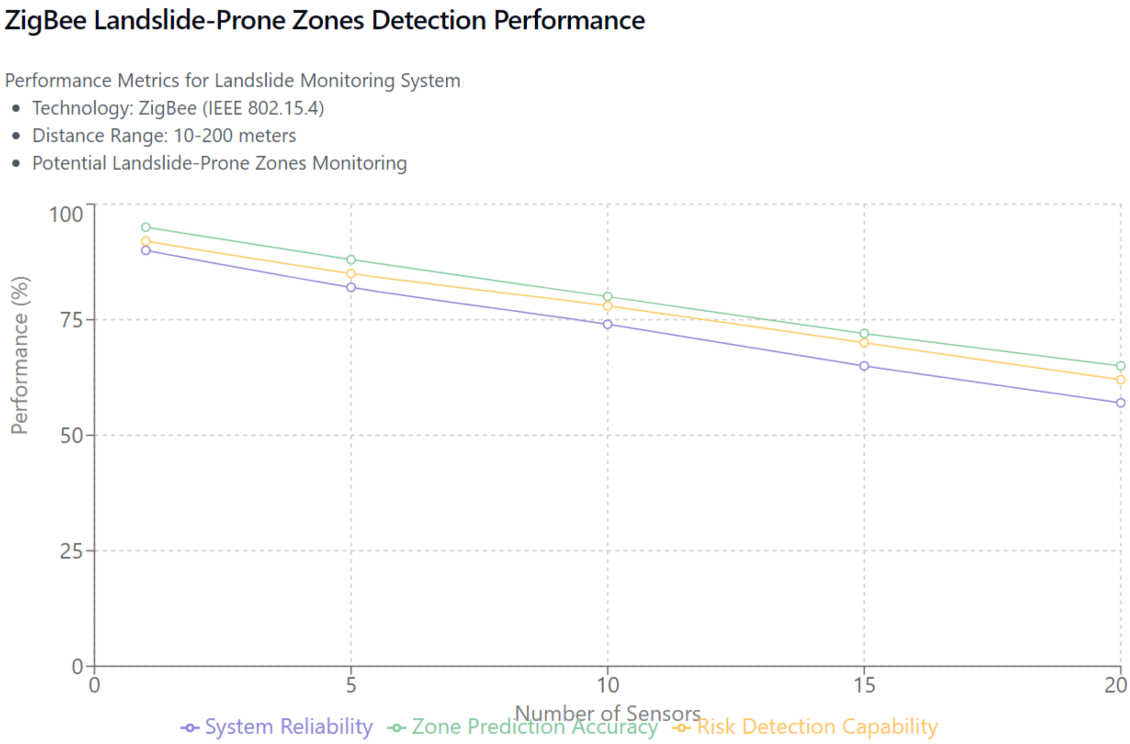

Figure 10.
Network Reliability of Potential landslide-prone zones.

Figure 10. shows that system reliability declines from 90% (1 sensor) to 57% (20 sensors), zone prediction accuracy drops from 95% to 65%, and risk detection capability reduces from 92% to 62%, with a communication range of 10 to 200 meters. Moreover, the performance characteristics show that there is an initial high performance with a single sensor, followed by gradual performance degradation as the sensor count increases, highlighting the significant impact of network complexity and communication range.

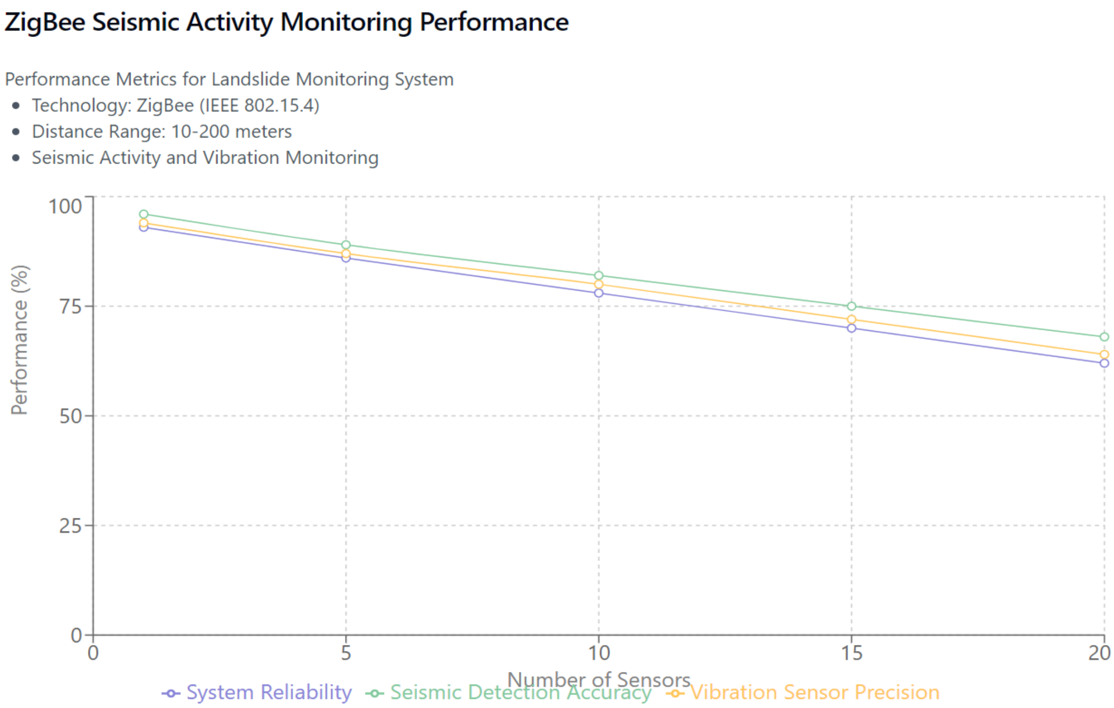

Figure 11.
Network Reliability of Seismic Activity.

4.3. Seismic activity

4.3.1. Performance Metrics

- Distance Range: 10 to 200 meters
- Number of Sensors: Up to 20
- Three key performance indicators plotted: a) System Reliability (purple line) b) Seismic Detection Accuracy (green line) c) Vibration Sensor Precision (yellow line)

Figure 11 shows that system reliability decreases from 93% (1 sensor) to 62% (20 sensors), seismic detection accuracy drops from 96% to 68%, vibration sensor precision reduces from 94% to 64%, and communication range from 10 to 200 meters. Moreover, the performance characteristics show that the highest performance with a single sensor, gradual and consistent performance degradation as sensor count increases, significant impact of network complexity and communication range

5. Conclusions

We concluded that signal strength progressively weakens with increasing slope angle and distance. Moreover, it describes that the system resilience maintains over 65% reliability even at maximum sensor count and distance, and demonstrates ZigBee IEEE 802.15.4 technology's robustness. For terrain impact, the slope angle correlation shows performance challenges in steeper terrains, and increased slope complexity affects signal propagation and sensor reliability. For soil composition, Sandy Loam provides the best signal transmission (least signal loss), lowest signal attenuation, and most consistent communication. Meanwhile, Rocky soil, it has the worst signal transmission (most signal loss). Moreover, both reliability and packet delivery ratio decreases as the number of sensors increases; the communication range spans from 10 to 200 meters, reliability drops from 85% (1 sensor) to 55% (20 sensors), and packet delivery ratio declines from 90% to 65%.

The RSSI (signal strength) progressively decreases; higher rainfall intensities cause more significant signal degradation, and signal strength drops more rapidly with increased distance and rainfall. Meanwhile, the signal strength ranges from -65 dBm to -110 dBm. System reliability decreases from 92% (1 sensor) to 60% (20 sensors), rain intensity detection drops from 98% to 70%, rain sensor accuracy reduces from 95% to 65%, and communication range spans from 10 to 200 meters.

The RSSI values for potential landslide-prone zones indicate that terrain stability impacts wireless communication, demonstrates the challenges of maintaining consistent sensor network performance, and provides insights into signal propagation in different geological contexts. System reliability declines from 90% (1 sensor) to 57% (20 sensors), zone prediction accuracy drops from 95% to 65%, risk detection capability reduces from 92% to 62%, and communication range spans from 10 to 200 meters.

Moreover, the RSSI values indicate the impact of seismic activity; at 10 meters, near-optimal signal strength is close to -20 dBm, around 100 meters signal quality enters the good-to-moderate range, and at 200 meters, the signal approaches the weak signal zone. System reliability decreases from 93% (1 sensor) to 62% (20 sensors), seismic detection accuracy drops from 96% to 68%, vibration sensor precision reduces from 94% to 64%, and communication range spans from 10 to 200 meters.

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