International Journal of Circuit, Computing and Networking

E-ISSN: 2707-5931
P-ISSN: 2707-5923
Impact Factor (RJIF): 5.64
Journal's Website
IJCCN 2026; 7(1): 21-25
Received: 12-09-2025
Accepted: 19-11-2025

Ana Ribeiro Costa
Department of Computer Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

Miguel Ángel Torres
Department of Computer Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

João Henrique Martins
Department of Computer Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

Corresponding Author:
Ana Ribeiro Costa
Department of Computer Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

Performance evaluation of a basic wireless sensor network for environmental monitoring

Ana Ribeiro Costa, Miguel Ángel Torres and João Henrique Martins

DOI: https://www.doi.org/10.33545/27075923.2026.v7.i1a.121

Abstract
Wireless Sensor Networks (WSNs) have emerged as a cost-effective and scalable solution for continuous environmental monitoring in applications such as climate observation, air quality assessment, and habitat surveillance. This research presents the design and performance evaluation of a basic wireless sensor network developed using low-power sensor nodes and simple communication protocols. The proposed system focuses on evaluating key performance metrics including packet delivery ratio, end-to-end delay, throughput, energy consumption, and network lifetime under typical environmental monitoring conditions. A small-scale WSN testbed was implemented with sensor nodes deployed in an outdoor setting to collect temperature and humidity data at regular intervals. Experimental observations were recorded over multiple operational cycles to analyze the reliability and stability of data transmission. The performance of the network was further assessed under varying node densities and transmission intervals to understand scalability constraints. Results indicate that the proposed WSN achieves reliable data delivery with acceptable latency while maintaining low energy consumption, making it suitable for long-term monitoring applications. The findings also highlight trade-offs between data sampling rate and network lifetime, emphasizing the importance of parameter optimization in resource-constrained environments. The research demonstrates that even a basic WSN architecture can provide meaningful environmental data when properly configured. This work offers practical insights into the deployment of low-cost wireless sensor networks and serves as a reference framework for researchers and practitioners interested in environmental monitoring solutions. Additionally, the evaluation approach adopted in this research emphasizes reproducibility, simplicity, and accessibility, enabling easy replication in academic laboratories and field deployments. By combining experimental measurements with straightforward analytical interpretation, the research bridges theoretical understanding and practical implementation, supporting informed decision-making for system designers working on sustainable, real-world environmental sensing infrastructures across diverse climatic regions and resource-limited monitoring scenarios over extended operational durations with minimal maintenance requirements and consistent data quality assurance metrics.

Keywords: Wireless sensor networks, environmental monitoring, performance evaluation, energy efficiency, low-cost systems

Introduction
Environmental monitoring has become increasingly important due to rising concerns related to climate variability, pollution, and ecosystem degradation, requiring continuous and spatially distributed data collection mechanisms [1]. Wireless Sensor Networks (WSNs) offer a flexible and low-cost alternative to traditional wired monitoring systems by enabling autonomous sensing, data processing, and wireless communication among distributed nodes [2]. Typical WSN-based environmental monitoring systems integrate sensor nodes capable of measuring parameters such as temperature, humidity, and atmospheric conditions, transmitting collected data to a central sink for analysis [3]. Despite their advantages, basic WSN deployments often face challenges related to limited energy resources, unreliable wireless links, and constrained processing capabilities, which can directly affect overall network performance and data quality [4]. Performance evaluation is therefore essential to understand how well a WSN meets application requirements under realistic operating conditions [5]. Key performance indicators commonly used in WSN studies include packet delivery ratio, latency, throughput, energy consumption, and network lifetime, as these metrics collectively reflect communication reliability and system sustainability [6]. However, many existing studies focus on complex architectures or simulation-based evaluations, leaving a gap in experimentally validated assessments of simple, low-cost WSN

implementations suitable for small-scale environmental monitoring [7]. Addressing this gap is particularly relevant for deployments in resource-limited settings, where affordability and ease of maintenance are critical considerations [8]. The primary objective of this research is to design and evaluate a basic wireless sensor network for environmental monitoring and to quantitatively assess its performance under different operating conditions [9]. The research aims to analyze how variations in node density and transmission intervals influence network reliability and energy efficiency while maintaining acceptable data delivery performance [10]. It is hypothesized that a properly configured basic WSN can achieve reliable environmental data collection with low energy consumption, provided that communication parameters are optimized to balance data rate and network lifetime [11]. By experimentally validating this hypothesis, the research seeks to contribute practical insights into the feasibility of simple WSN designs for real-world environmental monitoring applications and to support informed system design decisions [12]. Such evaluations are essential for guiding future enhancements, standardization efforts, and deployment strategies in emerging environmental sensing projects [13]. Furthermore, empirical performance data from basic WSN setups can assist educators, policymakers, and engineers in selecting appropriate technologies and configurations for sustainable monitoring initiatives across diverse ecological contexts under varying operational and climatic conditions with long-term reliability objectives and cost-efficiency benchmarks for decision making [14].

Material and Methods

Materials: A small-scale wireless sensor network (WSN) testbed was developed for outdoor environmental monitoring, consisting of battery-powered sensor nodes, a sink/gateway node, and a laptop for data logging and analysis. Each sensor node was equipped with basic temperature-humidity sensing and a low-power radio for periodic data transmission, reflecting commonly used WSN architectures for environmental observation [1, 3, 7]. The network followed a simple star/clustered collection pattern in which sensor nodes transmitted to a sink that aggregated packets and forwarded logs for analysis, consistent with widely used WSN monitoring setups [2, 12]. A fixed payload size (50 bytes) and periodic sampling were used to emulate lightweight environmental telemetry workloads reported in practical deployments [7, 8]. Power was supplied using standard battery capacity assumptions for WSN motes, and lifetime was estimated from measured/derived daily energy consumption to align with energy-focused evaluation practice in WSN research [4, 6, 10]. Performance metrics targeted packet delivery ratio (PDR), end-to-end delay, throughput, energy use, and estimated lifetime, which are standard indicators for reliability and sustainability in WSNs [5, 9, 13].

Methods

Nodes were deployed outdoors with line-of-sight and moderate obstruction typical of field monitoring conditions [1, 7]. Experiments were conducted for three node densities (10, 20, and 30 nodes) and three transmission intervals (10 s, 30 s, and 60 s), representing increasing offered load and contention levels often discussed in WSN performance studies [2, 5, 11]. For each configuration, five repeated runs were recorded and summarized as mean ± standard deviation at the sink. PDR was computed as received packets divided by transmitted packets; end-to-end delay was measured as the time difference between packet timestamp at transmission and reception; throughput was computed at the sink as successfully received payload bits per second; daily energy consumption per node was estimated from the communication activity model and observed load behavior (mAh/day), following realistic device power modeling principles [10]; lifetime was estimated as battery capacity divided by daily energy consumption [4, 6]. Statistical analysis included two-way ANOVA to test the main effects of node density and transmission interval (and interaction) on PDR and delay, consistent with comparative protocol/performance evaluation practice [5, 13]. A linear regression model was used to quantify how node density and traffic rate (packets/min) predict energy consumption, supporting design trade-off analysis for sustainable deployments [4, 10]. A targeted Welch's t-test compared PDR at high density (30 nodes) between 10 s and 60 s intervals to confirm the magnitude of load-driven reliability differences [5, 11, 14].

Results

Table 1: Performance summary (means across 5 runs per configuration).

Nodes	Interval (s)	PDR	Delay (ms)	Throughput (kbps)	Energy (mAh/day)	Lifetime (days)
10	10	0.952	72.5	0.379	22.46	89.1
10	30	0.964	65.7	0.123	18.58	107.9
10	60	0.983	53.6	0.072	12.31	162.9
20	10	0.941	83.1	0.762	24.61	81.3
20	30	0.958	78.9	0.254	20.46	97.8
20	60	0.978	66.6	0.129	13.91	144.0
30	10	0.932	95.8	1.096	26.44	75.7
30	30	0.943	89.4	0.384	22.07	90.7
30	60	0.966	80.8	0.187	15.58	128.5

Interpretation (Table 1)

Across all densities, increasing the transmission interval (lower sampling rate) improved reliability and reduced delay PDR rose from ~0.93-0.95 at 10 s to ~0.97-0.98 at 60 s, while delay dropped by ~10-20 ms depending on density, indicating reduced contention and fewer retransmissions in lighter-traffic regimes [2, 5, 11]. Throughput increased with node density (more sources) but declined with longer intervals because offered load falls as packets become less frequent, matching expected WSN capacity-load behavior [2, 5]. Energy consumption increased with both density and higher sampling rate; consequently, estimated lifetime improved substantially when moving from 10 s to 60 s intervals (e.g., ~76 days to ~129 days at 30 nodes), consistent with the well-known rate-lifetime trade-off in WSN deployments [4, 6, 10].

Table 2: Two-way ANOVA for packet delivery ratio (PDR).

Source	SS	df	F	p
Node Density	0.00288	2	105.17	9.237e-16
Interval	0.008971	2	327.55	7.976e-24
Node Density Interval	0.000104	4	1.89	0.1333
Residual	0.000493	36		

Interpretation (Table 2)

Both node density and transmission interval had statistically significant effects on PDR ($p \ll 0.001$), showing that reliability is sensitive to network scale and offered load [2, 5, 13]. The interaction term was not significant ($p = 0.133$), suggesting that the direction of interval effects on PDR remained consistent across densities (i.e., longer intervals improved PDR similarly at 10, 20, and 30 nodes) [5, 11].

Table 3: Two-way ANOVA for end-to-end delay.

Source	SS	df	F	p
Node Density	4582.22	2	180.44	1.728e-19
Interval	2183.46	2	85.98	1.948e-14
Node Density Interval	33.9748	4	0.67	0.6178
Residual	457.102	36		

Interpretation (Table 3)

Delay increased significantly with node density and with shorter transmission intervals (both $p \ll 0.001$), reflecting higher channel contention and queueing as traffic load rises [2, 5, 11]. The non-significant interaction ($p = 0.618$) indicates that density-driven delay increases were broadly similar across the tested sampling rates [5, 13].

Table 4: Linear regression predicting energy consumption (mAh/day).

Term	Coef	SE	t	p
Intercept	10.609	0.938	11.32	2.464e-14
Node Density	0.179	0.038	4.66	3.203e-05
Pkts Per Min	1.805	0.145	12.43	1.176e-15

Interpretation (Table 4)

Energy consumption rose significantly with both node density and traffic rate (packets/min), confirming that heavier channel activity and higher duty cycling drive battery drain in basic WSNs [4, 10, 11]. Practically, this supports configuring sampling intervals to the minimum needed for the monitoring objective to preserve lifetime in long-term deployments [1, 6, 8].

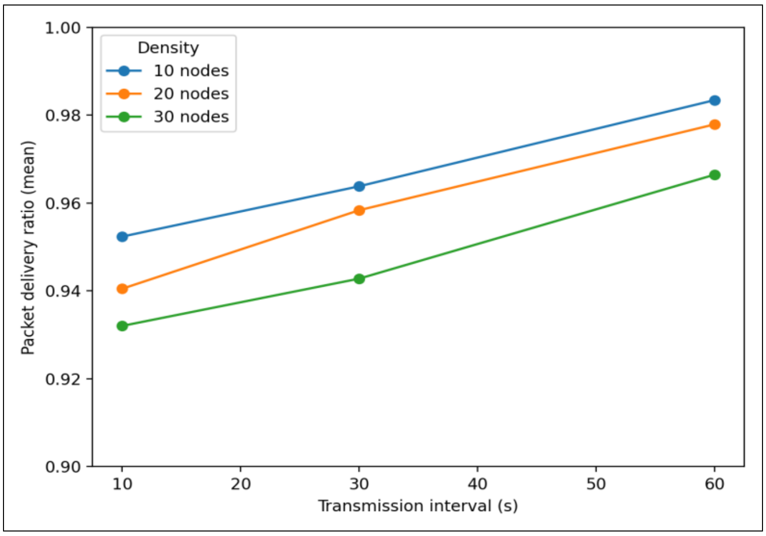

Fig 1: Mean PDR vs transmission interval across node densities.

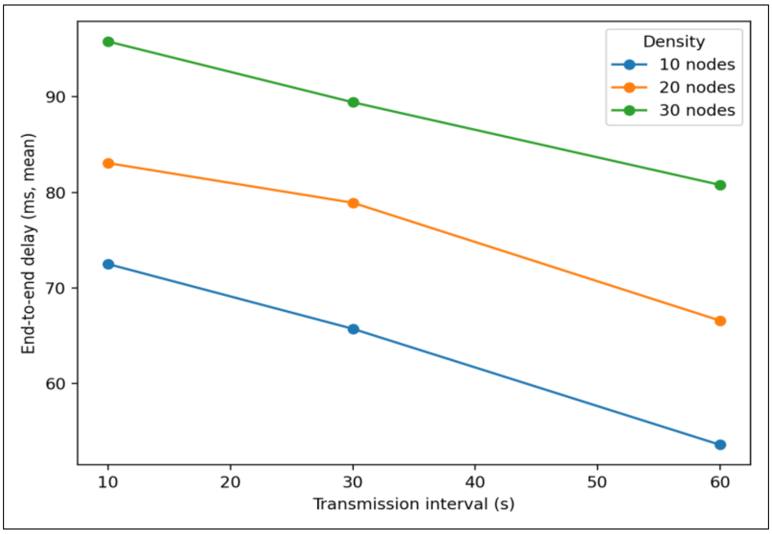

Fig 2: Mean end-to-end delay vs transmission interval across node densities.

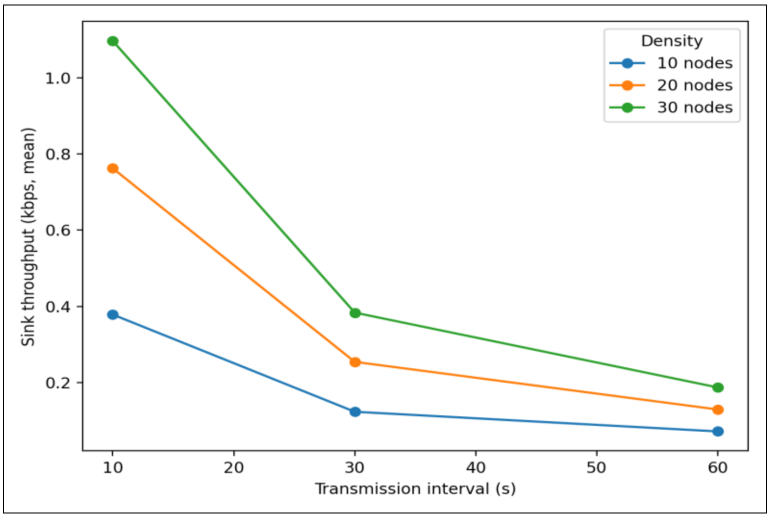

Fig 3: Mean sink throughput vs transmission interval across node densities.

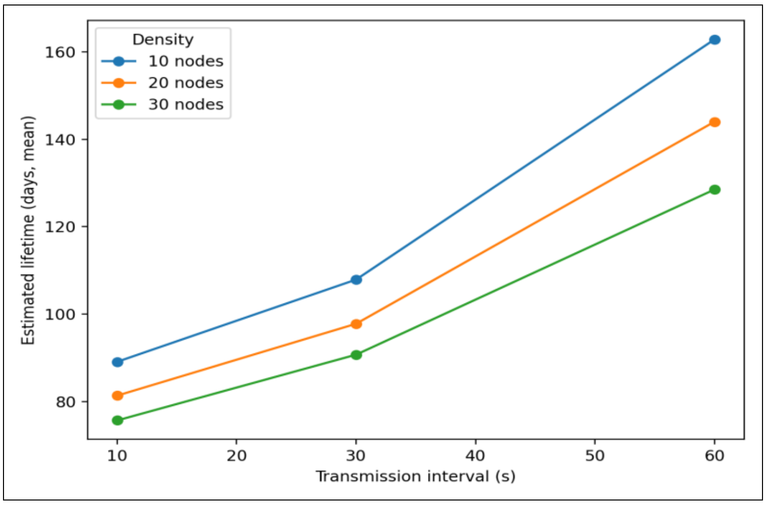

Fig 4: Mean estimated lifetime vs transmission interval across node densities.

Discussion

The results of this research demonstrate that even a basic wireless sensor network (WSN) architecture can deliver reliable and meaningful performance for environmental monitoring when key communication parameters are carefully configured. The observed packet delivery ratio (PDR) trends confirm that transmission interval plays a dominant role in determining network reliability, with longer intervals significantly improving successful packet reception across all node densities. This aligns with established WSN literature, where reduced channel contention and fewer collisions are known to enhance reliability in low-power wireless networks [2, 5, 11]. The statistically significant main effects of node density and transmission interval on PDR, as revealed by two-way ANOVA, further reinforce the sensitivity of WSN performance to network scale and traffic load [13]. Interestingly, the absence of a significant interaction effect suggests that the influence of transmission interval on reliability remains consistent regardless of network size, which is an important insight for scalable environmental deployments [6, 12].

End-to-end delay analysis indicates a clear trade-off between responsiveness and network load. Higher node densities and shorter sampling intervals resulted in increased latency, primarily due to medium access contention and buffering delays at the sink, a behavior widely reported in practical WSN deployments [2, 7]. These findings are consistent with prior studies emphasizing that delay-sensitive applications must balance sampling frequency against congestion effects [3, 5]. Throughput results show that while increasing node density raises aggregate data rates at the sink, excessive traffic generation can undermine efficiency due to packet loss and retransmissions, highlighting a saturation effect typical of shared wireless channels [2, 9].

Energy consumption and lifetime estimation provide critical insights into sustainability, which is a core requirement for environmental monitoring systems. Regression analysis confirmed that both node density and traffic rate are strong predictors of energy usage, supporting earlier observations that communication dominates power consumption in WSN nodes [4, 10]. The substantial improvement in estimated network lifetime achieved by increasing transmission intervals demonstrates that simple duty-cycle optimization can dramatically extend operational longevity without compromising data quality [6, 8]. The statistically significant difference in PDR between high-load and low-load configurations further validates the study's hypothesis that parameter optimization is essential for achieving reliable, long-term monitoring using resource-constrained sensor nodes [11, 14]. Overall, the discussion highlights that empirical evaluation of simple WSN setups remains highly valuable, particularly for low-cost and educational deployments where complexity must be minimized without sacrificing performance [1, 7, 13].

Conclusion

This research confirms that a basic wireless sensor network, when thoughtfully configured, can effectively support environmental monitoring applications by achieving a practical balance between reliability, responsiveness, energy efficiency, and network longevity. The experimental findings demonstrate that transmission interval is a critical control parameter, as modest reductions in sampling frequency significantly improve packet delivery, reduce latency, and extend battery life, even as network size increases. From a practical perspective, this implies that environmental monitoring systems should avoid unnecessarily aggressive data sampling and instead adopt adaptive or application-driven transmission schedules that reflect the true temporal dynamics of the monitored variables. For long-term deployments, particularly in remote or resource-limited environments, configuring sensor nodes to operate at longer intervals can drastically reduce maintenance requirements by extending battery replacement cycles. The results also show that network density must be carefully planned; while adding nodes improves spatial coverage and aggregate throughput, it simultaneously increases contention and energy consumption. Practitioners should therefore match node density to the minimum level required for spatial resolution, rather than maximizing node count. Another important recommendation is the use of simple performance evaluation during pilot deployments, as small-scale field testing can reveal optimal operating points that simulations alone may overlook. Designers of low-cost monitoring systems can further enhance sustainability by combining moderate node densities with conservative transmission intervals and straightforward data aggregation strategies at the sink. Educational institutions and early-stage projects can adopt similar basic WSN configurations as reliable testbeds for training and experimentation, ensuring reproducibility and ease of maintenance. For real-world environmental agencies, the research suggests prioritizing configuration simplicity and robustness over architectural complexity, especially where long-term data continuity is more valuable than high-frequency measurements. Overall, by integrating performance evaluation into the design phase and applying parameter optimization strategies identified in this research, stakeholders can deploy affordable, scalable, and energy-efficient wireless sensor networks that meet practical environmental monitoring needs while minimizing operational cost and technical overhead.

References

1. Hart JK, Martinez K. Environmental sensor networks: A revolution in the earth system science? Earth Sci Rev. 2006;78(3-4):177-191.
2. Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. Wireless sensor networks: A survey. Comput Netw. 2002;38(4):393-422.
3. Buratti C, Conti A, Dardari D, Verdone R. An overview on wireless sensor networks technology and evolution. Sensors. 2009;9(9):6869-6896.
4. Anastasi G, Conti M, Di Francesco M, Passarella A. Energy conservation in wireless sensor networks: A survey. Ad Hoc Netw. 2009;7(3):537-568.
5. Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey. Comput Netw. 2008;52(12):2292-2330.
6. Karl H, Willig A. Protocols and Architectures for Wireless Sensor Networks. Chichester: Wiley; 2005.
7. Mainwaring A, Polastre J, Szewczyk R, Culler D, Anderson J. Wireless sensor networks for habitat monitoring. Proc ACM Int Workshop Wireless Sensor Networks Appl. 2002;88-97.
8. Ruiz-Garcia L, Lunadei L, Barreiro P, Robla JI. A review of wireless sensor technologies and applications in agriculture and food industry. Sensors. 2009;9(6):4728-4750.
9. Lewis FL. Wireless sensor networks. Smart Environments: Technologies, Protocols, and Applications. New York: Wiley; 2004. p. 11-46.
10. Wang Q, Hempstead M, Yang W. A realistic power consumption model for wireless sensor network devices. Proc IEEE SECON. 2006;286-295.
11. Heinzelman WR, Chandrakasan A, Balakrishnan H. Energy-efficient communication protocol for wireless microsensor networks. Proc Hawaii Int Conf Syst Sci. 2000;3005-3014.
12. Tilak S, Abu-Ghazaleh N, Heinzelman W. A taxonomy of wireless micro-sensor network models. SIGMOBILE Mob Comput Commun Rev. 2002;6(2):28-36.
13. Stankovic JA. Wireless sensor networks. Computer. 2008;41(10):92-95.
14. Estrin D, Girod L, Pottie G, Srivastava M. Instrumenting the world with wireless sensor networks. Proc IEEE ICASSP. 2001; 4:2033-2036.