
| RESEARCH ARTICLE

Performance Evaluation of Layered Min-Sum LDPC Decoding in Wireless Sensor Networks over AWGN, Rayleigh, and Multipath Fading Channels

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| ABSTRACT

Wireless sensor networks require reliable and energy-efficient error-control techniques because sensor nodes operate under constrained energy resources and variable wireless channel conditions. This study evaluates a Layered Min-Sum (LMS) LDPC decoder with Early Stopping over AWGN, frequency-flat Rayleigh, and frequency-selective Multipath fading channels. A rate-1/2 (16,8) LDPC code with BPSK modulation was simulated in MATLAB using 1,600 information bits over Eb/N0 values of 1–9 dB. Performance was assessed using BER, average decoding iterations, and estimated decoding energy per bit (DEB). AWGN achieved the best overall performance, with mean BER, iterations, and DEB of 0.0170, 2.1470, and 0.1503 nJ/bit, respectively. Rayleigh and Multipath fading produced higher mean BERs of 0.0671 and 0.2034, respectively. The results demonstrate that fading conditions substantially influence LDPC decoding reliability, computational effort, and energy consumption.

| KEYWORDS

Layered Min-Sum decoding, LDPC codes, Wireless sensor networks, Rayleigh fading, Multipath fading.

| ARTICLE INFORMATION

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1. Introduction

Wireless Sensor Networks (WSNs) have become an important component of modern communication and Internet-of-Things (IoT) systems, supporting applications such as environmental monitoring, healthcare, industrial automation, agriculture, surveillance, and smart infrastructure [Sai, 2017, Ali, 2023, Kamal, 2015, Nourildean, 2022, Zijie, 2023]. A WSN typically consists of distributed sensor nodes that sense, process, and wirelessly transmit information to a sink or base station. However, the limited battery capacity, processing capability, memory, and communication resources of sensor nodes make energy efficiency a critical design consideration [Kamal, 2015, Alrajeh, 2015, Abdulwahid, 2021]. This challenge becomes more significant when sensor nodes are deployed in remote or difficult-to-access environments, where frequent battery replacement is impractical.

Wireless transmission is vulnerable to noise, interference, attenuation, and other channel impairments that can corrupt transmitted information and reduce communication reliability [Xu, 2022, Arora, 2016, Faris, 2023]. Forward Error Correction (FEC) improves reliability by introducing controlled redundancy that enables receivers to detect and correct errors without requiring retransmission. Although FEC can reduce retransmission-related energy consumption, error-correcting codes themselves introduce computational and energy overhead. Consequently, ECC selection requires a balance among error-correction capability, decoding complexity, energy consumption, and reliability [Pandey, 2015, Patil, 2017, Kundaali, 2020].

Several ECC families, including BCH, Reed-Solomon (RS), convolutional, and Low-Density Parity-Check (LDPC) codes, have been investigated for wireless communication systems [Tiwari, 2015, Mohamed, 2017, Spyrou, 2022]. BCH codes provide effective correction of multiple errors, while Reed-Solomon codes are particularly suitable for burst-error correction. Convolutional codes offer relatively simple decoding, whereas LDPC codes provide strong error-correction capability and can achieve performance close to the theoretical limits of communication channels [Yang, 2024]. However, the iterative nature of LDPC decoding can impose substantial computational and energy costs, making decoder optimization particularly important for resource-constrained wireless systems [Alrajeh, 2015, Yang, 2024].

The Min-Sum algorithm provides a lower-complexity alternative to the conventional Sum-Product Algorithm by replacing computationally intensive probability operations with simpler minimum and sign operations. Venkatesan et al. [2016] demonstrated the low-power potential of Min-Sum decoding through an ASIC implementation of an LDPC decoder. However, their implementation employed a fixed number of decoding iterations and did not incorporate an adaptive early-stopping mechanism. Consequently, decoding operations could continue even after the parity-check conditions had been satisfied, resulting in unnecessary computational activity and energy expenditure.

Layered Min-Sum (LMS) decoding provides another means of improving LDPC decoding efficiency by processing the parity-check matrix layer by layer and immediately updating the associated variable-node information. This enables reliability information to propagate more rapidly through the decoding graph and can reduce the number of iterations required for convergence. Combining LMS with Early Stopping (ES) can further reduce unnecessary decoding operations by terminating the iterative process once the estimated codeword satisfies the required parity-check conditions.

Building on these concepts, Onyeonwu et al. [2016] developed an energy-efficient LDPC decoding approach based on Layered Min-Sum and Early Stopping. The study evaluated the developed decoder using MATLAB with BPSK modulation over an Additive White Gaussian Noise (AWGN) channel and compared it with conventional Flooding Min-Sum decoding. Performance was assessed using Bit Error Rate (BER), Decoding Energy per Bit (DEB), and decoding iteration count over E_b/N_0 values from 1 to 9 dB [19]. The results showed that LMS with Early Stopping substantially improved decoding efficiency. Specifically, the mean decoding energy per bit decreased from 1.2960 nJ/bit for Flooding Min-Sum to 0.7174 nJ/bit for LMS with Early Stopping, while the mean number of iterations decreased from 18.40 to 10.23 [Onyeonwu, 2026]. These findings demonstrate the potential of combining layered decoding with early termination to reduce LDPC decoding energy.

Despite these encouraging results, the previous investigation was limited to the AWGN channel. Although AWGN provides a useful baseline for communication-system analysis, it does not adequately represent propagation effects such as multipath and fading encountered in practical wireless environments. Wireless channel characteristics can vary with propagation conditions, producing changes in received signal strength and communication reliability [BenSaleh, 2020, Kadel, 2020]. Such variations can affect the reliability of the soft information supplied to an iterative decoder and consequently influence both BER and the number of iterations required for convergence.

Channel-adaptive error-control studies have emphasized the importance of considering changing wireless conditions when designing reliable and energy-efficient WSN communication systems [Patil, 2017, Khan, 2020]. Adaptive error-control strategies can adjust coding and other transmission parameters according to channel conditions, thereby avoiding unnecessary redundancy under favourable conditions while providing adequate protection under poor conditions [Patil, 2017, Khan, 2020]. Therefore, an LDPC decoding strategy that demonstrates improved energy efficiency under AWGN should also be evaluated under representative fading conditions to determine how channel impairments affect its reliability, decoding complexity, and energy consumption.

The existing literature therefore reveals a gap in the evaluation of energy-efficient LMS LDPC decoding. Alrajeh et al. [2015] established the high error-correction capability but relatively high energy cost of LDPC decoding, while Venkatesan et al. [2016] demonstrated the low-power potential of Min-Sum decoding using a fixed iteration strategy. The previous study by Onyeonwu et al. [2026] addressed the latter limitation through the combination of LMS and Early Stopping, but its evaluation was restricted to AWGN. It remains unclear whether the energy and decoding-efficiency benefits observed under AWGN persist under fading and multipath conditions.

This study therefore evaluates the performance of the Layered Min-Sum LDPC decoder with Early Stopping over Rayleigh and Multipath fading channels. The analysis considers BER, Decoding Energy per Bit, and decoding iteration count over varying E_b/N_0 conditions, using the AWGN results as a baseline. The study extends the authors' previous investigation and provides further insight into the robustness and energy efficiency of LMS LDPC decoding for reliable WSN communication under more realistic wireless channel conditions.

2. Methodology

2.1 Simulation Framework

The study employed a MATLAB-based simulation framework to evaluate the performance of a Layered Min-Sum (LMS) Low-Density Parity-Check (LDPC) decoder with Early Stopping under three channel conditions: Additive White Gaussian Noise (AWGN), frequency-flat Rayleigh fading, and frequency-selective multipath Rayleigh fading. The simulation retained the LDPC configuration and decoding approach used in the preceding study while extending the channel environment beyond AWGN. Performance was evaluated using Bit Error Rate (BER), average decoding iteration count, and Decoding Energy per Bit (DEB).

2.2 LDPC Encoding and Modulation

A rate-1/2 LDPC code with block length $n = 16$ and information length $k = 8$ was used. The information sequence was encoded using the parity-check/generator matrix configuration employed in the established MATLAB implementation. The encoded codewords were modulated using BPSK, with the mapping $0 \rightarrow +1$ and $1 \rightarrow -1$. A total of 1,600 information bits was simulated for each channel condition, corresponding to 200 LDPC blocks of 8 information bits each. The resulting 3,200 coded bits were transmitted using BPSK modulation at E_b/N_0 values of 1, 3, 5, 7, and 9 dB.

2.3 Channel Models

Three channel conditions were considered. The AWGN channel was used as the baseline and was represented by the received-signal model $y = x + n$. A frequency-flat Rayleigh channel was then considered using one fading path with zero delay and 0 dB average path gain. Finally, a frequency-selective three-path Rayleigh channel was used to represent multipath propagation. The three paths had delays of 0, 1, and 3 μs and average path gains of 0, -3, and -6 dB, respectively. The fading channels used a Jakes Doppler spectrum with a maximum Doppler shift of 30 Hz. A sampling frequency of 1 MHz and normalized path gains were used for the fading-channel simulations.

2.4 Channel Information and Soft-Decision Processing

Perfect channel state information (CSI) was assumed at the receiver for the Rayleigh and Multipath experiments. The instantaneous channel response was therefore used for channel equalization before the soft information was supplied to the LDPC decoder. The received signals were converted to log-likelihood ratios (LLRs), with the noise variance and instantaneous fading coefficient taken into account in the fading-channel cases. The use of perfect CSI

allowed the study to isolate the effect of the propagation channel on decoder performance without introducing additional channel-estimation errors or pilot overhead.

For the frequency-selective multipath channel, MMSE equalization was applied using the known channel frequency response. The MMSE equalizer was defined as

$$W_{MMSE}(f) = H^*(f) / (|H(f)|^2 + N_0/E_s) \quad (1)$$

where $H(f)$ denotes the channel frequency response, N_0 is the noise power spectral density, and E_s is the transmitted symbol energy. The equalized signal was obtained as

$$\hat{X}(f) = W_{MMSE}(f)Y(f) \quad (2)$$

before LLR computation. Perfect CSI was assumed at the receiver.

2.5 Layered Min-Sum Decoding with Early Stopping

The received LLRs were decoded using the Layered Min-Sum algorithm. The parity-check matrix was processed sequentially by layers, and updated variable-node information was immediately used by subsequent layers. For each check node, the Min-Sum rule determined the outgoing message from the signs and minimum magnitudes of the incoming messages. A maximum of 50 decoding iterations was permitted.

Early Stopping was applied after each complete decoding iteration. Hard decisions were obtained from the current LLR values and the syndrome was evaluated as $s = H\hat{c}^T \bmod 2$. When the syndrome was zero, the parity-check constraints were satisfied and decoding was terminated. Otherwise, decoding continued until convergence or the maximum iteration limit was reached. This adaptive termination reduced unnecessary iterations for successfully decoded blocks. The iteration count included the complete decoding iteration during which the syndrome was evaluated; therefore, a successfully decoded block after its first iteration was recorded as requiring one iteration.

2.6 Simulation Parameters and Performance Measures

Table 1. Simulation Parameters

Parameter	AWGN	Rayleigh	Multipath Rayleigh
Channel type	AWGN	Frequency-flat Rayleigh	Frequency-selective 3-path Rayleigh
Number of paths	—	1	3
Path delays	—	0 μ s	0, 1, 3 μ s
Average path gains	—	0 dB	0, -3, -6 dB
Doppler spectrum	—	Jakes	Jakes
Maximum Doppler shift	—	30 Hz	30 Hz
Path-gain normalization	—	Enabled	Enabled
Channel estimation	—	Perfect CSI	Perfect CSI
Sampling frequency	1 MHz	1 MHz	1 MHz
Modulation	BPSK	BPSK	BPSK
LDPC code	(16,8)	(16,8)	(16,8)
Code rate	1/2	1/2	1/2
Information bits	1600	1600	1600
Blocks per E_b/N_0	200	200	200
Coded bits	3200	3200	3200
E_b/N_0	1, 3, 5, 7, 9 dB	1, 3, 5, 7, 9 dB	1, 3, 5, 7, 9 dB
Maximum decoder iterations	50	50	50
Decoder	LMS + Early Stopping	LMS + Early Stopping	LMS + Early Stopping
Primary metrics	BER, Iterations, DEB	BER, Iterations, DEB	BER, Iterations, DEB

BER was calculated as the ratio of incorrectly decoded information bits to the total transmitted information bits. The average iteration count was obtained from the total number of iterations required by the simulated blocks. The decoding energy per bit (DEB) was estimated based on the average number of decoding iterations, following the energy model established by Onyeonwu et al. [2026]. An energy consumption of 0.0700 nJ/bit/iteration was adopted for one decoding iteration [Onyeonwu et al, 2026]. Thus, the decoding energy per bit was calculated as

$$\text{DEB} = \text{Niter} \times \text{Eiter} \quad (3)$$

Where Eiter = 0.0700nJ/bit/iteration and Niter is the average number of decoding iterations.

Then DEB = 0.0700Niter

This model accounts for the effect of the Early Stopping mechanism, whereby favorable channel conditions require fewer iterations and consequently lower decoding energy, while adverse channel conditions may require more iterations and higher energy consumption. The same energy model was applied consistently to the AWGN, Rayleigh, and Multipath fading simulations. The energy analysis in this study is restricted to LDPC decoding energy; transmission, encoding, and retransmission energies are outside the scope of the present evaluation.

2.7 Comparative Evaluation

The three channel conditions were evaluated using identical LDPC, modulation, simulation, and decoder parameters. BER, average iteration count, and DEB were obtained at each E_b/N_0 value. Comparative line plots and grouped bar charts were generated for the three performance measures, while mean values across the five E_b/N_0 operating points were also calculated. The resulting performance differences were used to determine the effect of Rayleigh and multipath fading on the reliability, computational workload, and energy efficiency of the LMS LDPC decoder.

The simulations were implemented in MATLAB R2019a. The specified fading-channel parameters were treated as controlled simulation conditions rather than measurements of a particular geographical propagation environment, thereby allowing reproducible comparison with the AWGN baseline.

3. Results

The performance of the Layered Min-Sum (LMS) LDPC decoder with Early Stopping was evaluated under three channel conditions: Additive White Gaussian Noise (AWGN), Rayleigh fading, and multipath Rayleigh fading. The evaluation was conducted at E_b/N_0 values of 1, 3, 5, 7, and 9 dB. The performance indicators considered were Bit Error Rate (BER), decoding iteration count, and Decoding Energy per Bit (DEB). The results are presented and compared in the following subsections.

3.1 BER Performance

Figures 1 and 2 present the BER results for the three channel conditions.

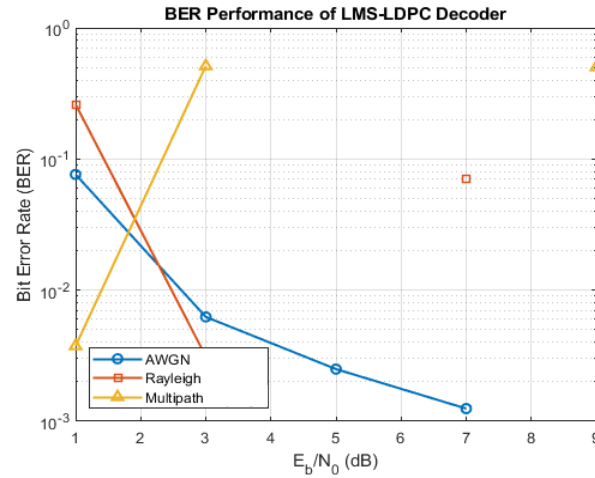


Figure 1. BER versus E_b/N_0 for LMS-LDPC decoding under AWGN, Rayleigh, and Multipath channels.

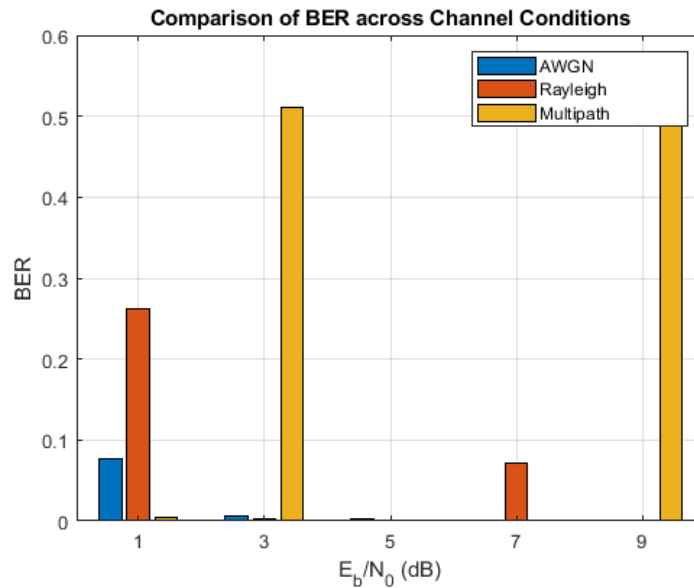


Figure 2. Comparative BER performance of LMS-LDPC decoding under the three channel conditions.

Table 2: BER Performance of LMS-LDPC Decoder

E_b/N_0 (dB)	AWGN	Rayleigh	Multipath Rayleigh
1	0.07625	0.26125	0.00375
3	0.00625	0.003125	0.51125
5	0.00250	0.00000	0.00000
7	0.00125	0.07125	0.00000
9	0.00000	0.00000	0.501875
Mean	0.01725	0.067125	0.203375

The BER results for the three channel conditions are presented in Table 2. The results show that the channel model has a considerable influence on the error performance of the LMS-LDPC decoder. For the AWGN channel, BER decreased consistently as E_b/N_0 increased. The BER reduced from 7.625×10^{-2} at 1 dB to 6.25×10^{-3} , 2.50×10^{-3} ,

and 1.25×10^{-3} at 3, 5, and 7 dB, respectively, before reaching zero at 9 dB. This represents the most consistent BER improvement among the three channel conditions.

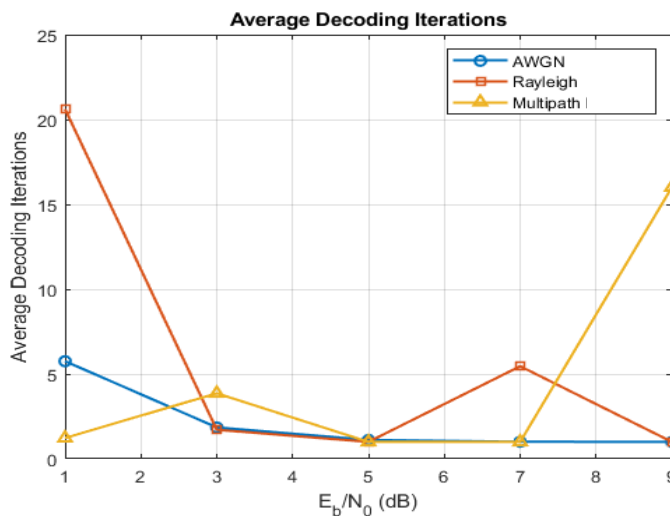
The Rayleigh channel exhibited a mean BER of 0.067125. At 1 dB, it recorded the highest BER of 0.26125, indicating the significant degradation caused by fading under low signal-to-noise conditions. The BER subsequently decreased to 0.003125 at 3 dB and reached zero at 5 dB. However, the BER increased again to 0.07125 at 7 dB before returning to zero at 9 dB. The non-monotonic behaviour reflects the stochastic nature of the fading process and the finite number of simulated information bits, under which individual channel realizations can produce variations in the observed BER across E_b/N_0 points. Nevertheless, the Rayleigh channel exhibited a higher mean BER than AWGN, indicating an overall degradation in decoding reliability due to fading.

The multipath Rayleigh channel produced the highest overall mean BER of 0.203375. Although its BER was relatively low at 1 dB (0.00375) and became zero at 5 and 7 dB, substantially higher BER values of 0.51125 and 0.501875 were obtained at 3 and 9 dB, respectively. The non-monotonic BER pattern is attributable to the stochastic nature of the multipath fading process and the finite simulation sample, which can result in substantial variation in the number of errors observed at individual E_b/N_0 operating points. Therefore, the individual BER values should be interpreted together with the mean BER, which indicates that multipath Rayleigh produced the poorest overall reliability among the three channel conditions.

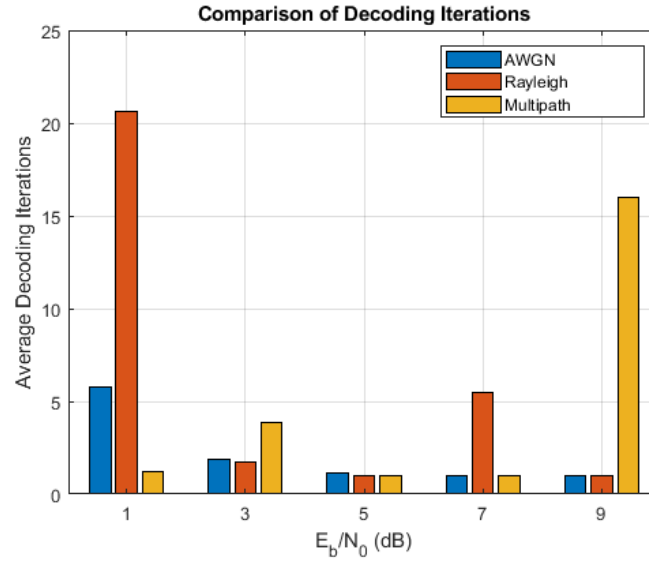
The mean BER results provide a more representative basis for comparing the overall performance across the five simulated E_b/N_0 operating points. AWGN provided the best overall error performance, followed by Rayleigh fading and then multipath Rayleigh fading. The mean BER of the Rayleigh channel was approximately 3.9 times that of AWGN, while the multipath Rayleigh channel produced approximately 11.8 times the AWGN mean BER. These results demonstrate that, despite variations at individual E_b/N_0 points, the fading and multipath channel conditions resulted in substantially poorer overall decoding reliability than the AWGN baseline.

3.2 Decoding Iteration Count

Figures 3 and 4 present the decoding iteration counts for the three channel conditions.



Figures 3. Average Iteration Count versus E_b/N_0 for LMS-LDPC decoding under AWGN, Rayleigh, and Multipath channels.



Figures 4. Comparative Decoding Iteration Count performance of LMS-LDPC decoding under the three channel conditions.

Table 3: Decoding Iteration Count

E_b/N_0 (dB)	AWGN	Rayleigh	Multipath Rayleigh
1	5.755	20.610	1.230
3	1.855	1.715	3.865
5	1.115	1.000	1.000
7	1.010	5.460	1.000
9	1.000	1.000	16.005
Mean	2.147	5.957	4.620

Table 3 presents the average number of decoding iterations required by the LMS-LDPC decoder before satisfying the Early Stopping condition. The number of iterations provides an indication of the computational effort required by the decoder and consequently has a direct relationship with decoding energy consumption.

The AWGN channel required the lowest average number of iterations, with a mean of 2.147 iterations. Its iteration count decreased from 5.755 at 1 dB to 1.855 at 3 dB and further to 1.115 at 5 dB. At 7 and 9 dB, the decoder required approximately one iteration, with values of 1.010 and 1.000, respectively. This behaviour indicates rapid convergence as the quality of the received signal improved.

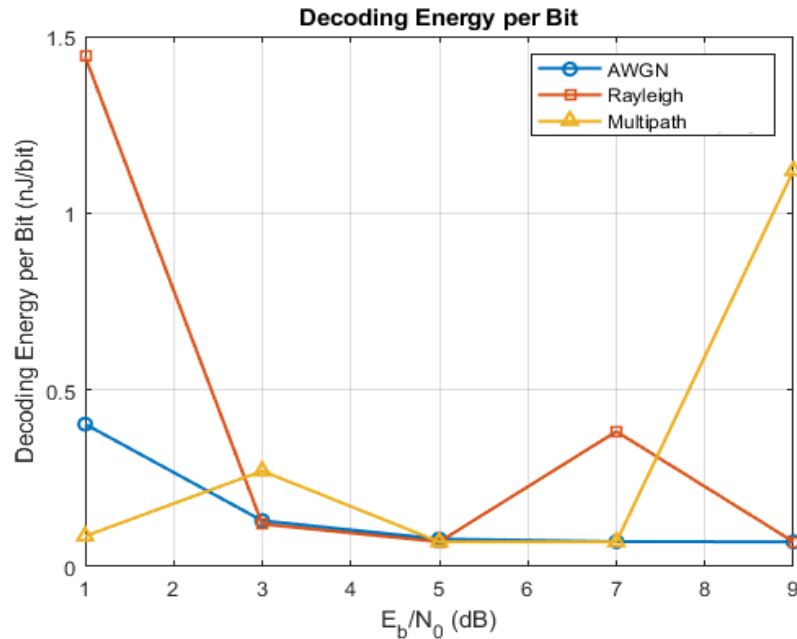
The Rayleigh channel required considerably more decoding effort at some operating points. Its highest iteration count of 20.610 occurred at 1 dB, corresponding to the channel's highest BER at that E_b/N_0 . The iteration counts subsequently decreased to 1.715 at 3 dB and reached 1.000 at 5 dB. However, it increased again to 5.460 at 7 dB before returning to 1.000 at 9 dB. The resulting mean iteration count was 5.957, the highest among the three channels.

For the multipath Rayleigh channel, the mean iteration count was 4.620. The decoder required 1.230 iterations at 1 dB and 3.865 iterations at 3 dB, while only one iteration was required at both 5 and 7 dB. At 9 dB, however, the iteration count increased substantially to 16.005. This increase corresponds with the high BER obtained at the same operating point.

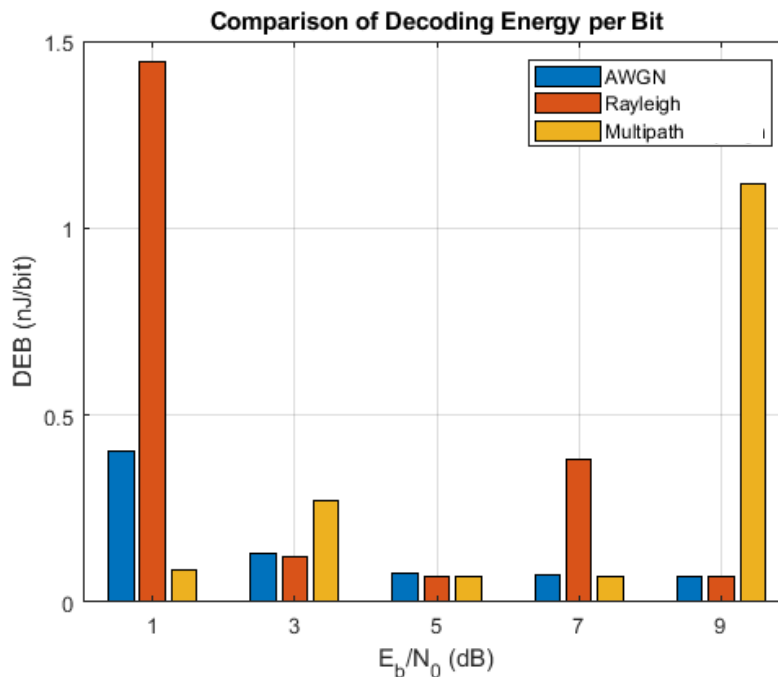
The results confirm that the Early Stopping mechanism can terminate decoding after relatively few iterations when the received information satisfies the parity-check conditions. However, under adverse or highly variable channel conditions, more iterations may be required before convergence is achieved. Compared with AWGN, the Rayleigh channel required approximately 177.5% more iterations on average, while multipath Rayleigh required approximately 115.2% more.

3.3 Decoding Energy per Bit

Figures 5 and 6 present the DEB results for the three channel conditions.



Figures 5. DEB versus E_b/N_0 for LMS-LDPC decoding under AWGN, Rayleigh, and Multipath channels.



Figures 6. Comparative DEB performance of LMS-LDPC decoding under the three channel conditions.

Table 4: Decoding Energy per Bit

Eb/N0 (dB)	AWGN (nJ/bit)	Rayleigh (nJ/bit)	Multipath Rayleigh (nJ/bit)
1	0.4029	1.4427	0.0861
3	0.1299	0.1201	0.2706
5	0.0781	0.0700	0.0700
7	0.0707	0.3822	0.0700
9	0.0700	0.0700	1.1203
Mean	0.1503	0.4170	0.3234

The DEB results are presented in Table 4. Since the proposed decoder's energy consumption is related to the number of decoding operations, variations in iteration count are reflected in the estimated DEB.

For the AWGN channel, DEB decreased progressively with increasing Eb/N0. It reduced from 0.4029 nJ/bit at 1 dB to 0.1299 nJ/bit at 3 dB and 0.0781 nJ/bit at 5 dB. At 7 and 9 dB, the DEB values were 0.0707 and 0.0700 nJ/bit, respectively. The mean DEB for AWGN was therefore only 0.1503 nJ/bit.

The Rayleigh channel recorded a mean DEB of 0.4170 nJ/bit. Its highest energy consumption, 1.4427 nJ/bit, occurred at 1 dB, where the decoder also recorded its highest iteration count of 20.610. The DEB subsequently reduced to 0.1201 nJ/bit at 3 dB and 0.0700 nJ/bit at 5 dB. It increased to 0.3822 nJ/bit at 7 dB and returned to 0.0700 nJ/bit at 9 dB.

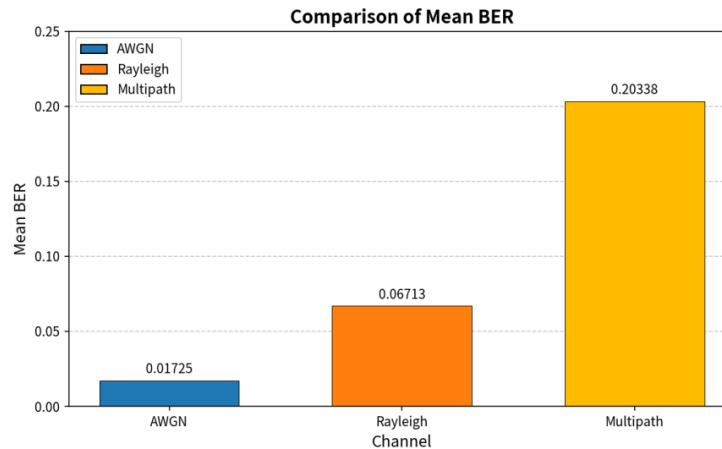
The multipath Rayleigh channel produced a mean DEB of 0.3234 nJ/bit. The lowest values of 0.0700 nJ/bit were recorded at 5 and 7 dB, where only one decoding iteration was required. However, DEB increased considerably to 1.1203 nJ/bit at 9 dB as the iteration count increased to 16.005.

The relationship between iteration count and DEB is evident from the results. The highest DEB values occurred at operating points where the decoder required substantially more iterations. For example, Rayleigh recorded 20.610 iterations and 1.4427 nJ/bit at 1 dB, while multipath Rayleigh recorded 16.005 iterations and 1.1203 nJ/bit at 9 dB. Conversely, the one-iteration cases generally resulted in the minimum DEB of approximately 0.0700 nJ/bit.

3.4 Comparative Performance of the Three Channels

Figures 7, 8 and 9, present the summary of the mean performance of the LMS-LDPC decoder for the three channel conditions.

Figure 7. Summary of the mean BER performance of the LMS-LDPC decoder for the three channel conditions.



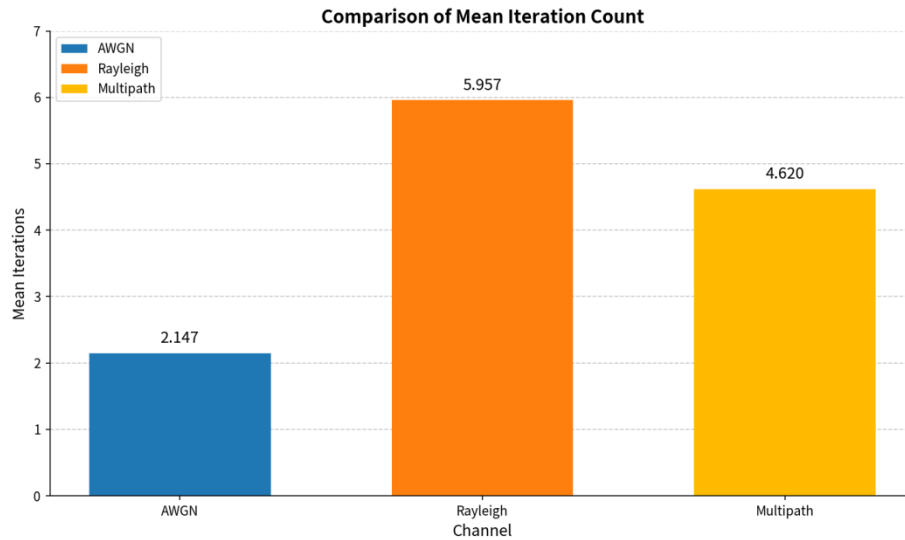


Figure 8. Summary of the mean Iteration Count performance of the LMS-LDPC decoder for the three channel conditions.

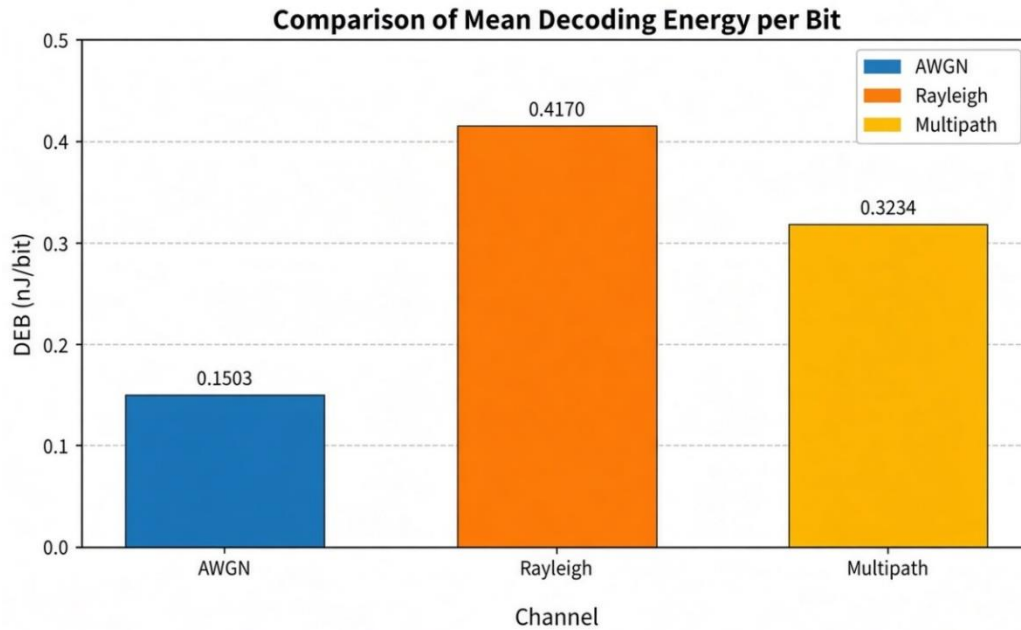


Figure 9. Summary of the mean DEB performance of the LMS-LDPC decoder for the three channel conditions.

Table 5: Mean Comparative Performance

Channel	Mean BER	Mean Iterations	Mean DEB (nJ/bit)
AWGN	0.01725	2.147	0.1503
Rayleigh	0.067125	5.957	0.4170
Multipath Rayleigh	0.203375	4.620	0.3234

Table 5 summarizes the mean performance of the LMS-LDPC decoder across the five E_b/N_0 values. AWGN produced the best overall performance, with the lowest mean BER (0.01725), lowest mean iteration count (2.147), and lowest mean DEB (0.1503 nJ/bit).

Rayleigh fading produced a mean BER of 0.067125, which was higher than the AWGN value, and required the highest average decoding effort of 5.957 iterations. This resulted in the highest mean DEB of 0.4170 nJ/bit. The multipath Rayleigh channel recorded the highest mean BER of 0.203375, indicating the poorest overall error performance. Its mean iteration counts of 4.620 and DEB of 0.3234 nJ/bit were nevertheless lower than those obtained for Rayleigh fading.

These results show that channel conditions have a significant effect on the reliability, decoding complexity, and estimated decoding energy of the LMS-LDPC decoder.

4. Conclusion

This study evaluated the performance of a Layered Min-Sum LDPC decoder with Early Stopping under AWGN, frequency-flat Rayleigh, and frequency-selective Multipath fading channel conditions. Using a rate-1/2 (16,8) LDPC code and BPSK modulation, the decoder was evaluated in terms of BER, average decoding iterations, and estimated decoding energy per bit across E_b/N_0 values from 1 to 9 dB. The AWGN channel provided the best overall performance, recording a mean BER of 0.0173, mean iteration count of 2.1470, and mean DEB of 0.1503 nJ/bit. Rayleigh fading increased the mean BER to 0.0671 and produced the highest mean decoding effort of 5.9570 iterations and 0.4170 nJ/bit. Multipath channel produced the highest mean BER of 0.2034, although its mean iteration count and DEB were lower than those of the frequency-flat Rayleigh channel.

The results also demonstrate that BER and decoding effort can exhibit non-monotonic behaviour under stochastic fading, particularly for the finite simulation sample used in this study. Nevertheless, the mean results consistently show that fading and multipath propagation impose greater reliability and decoding-energy challenges than the AWGN baseline. The Early Stopping mechanism reduced unnecessary iterations when parity-check conditions were satisfied, while adverse channel conditions increased the computational effort and corresponding DEB. Overall, the findings highlight the importance of evaluating energy-efficient LDPC decoding beyond AWGN when designing reliable wireless sensor network communication systems.

5. Recommendations

Based on the findings of this study, the following recommendations are proposed:

- i. Examine a broader range of Doppler spreads, multipath delay profiles, and fading distributions that better represent the diverse environments in which wireless sensor networks are deployed.
- ii. Validate the simulation-based energy model against actual hardware measurements on FPGA or ASIC platforms to confirm the absolute decoding-energy figures under the same channel conditions.
- iii. Investigate adaptive decoder parameters and iteration limits that respond to instantaneous channel conditions to further reduce decoding energy while maintaining the required BER performance.

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Artificial Intelligence (AI) Use Disclosure: The authors declare that no artificial intelligence tools were used in the preparation of this manuscript.

References

- [1] Abdulwahid A. H. and Salih M. J., (2021) Wireless sensor networks applications, challenges, and security requirements, in *Proc. 2nd Int. Multi-Disciplinary Conf. Integrated Sciences and Technologies (IMDC-IST)*, Sakarya, Turkey, Sep. 7–9, 2021, doi: 10.4108/eai.7-9-2021.2314823.

- [2] Ali M. M., Hashim S. J., Chaudhary M. A., Ferré G., Rokhani F. Z., and Ahmad Z., (2023) A reviewing approach to analyze the advancements of error detection and correction codes in channel coding with emphasis on LPWAN and IoT systems, *IEEE Access*, vol. 11, pp. 127077–127097, 2023, doi: 10.1109/ACCESS.2023.3331417.
- [3] Alrajeh N. A., Marwat U., Shams B., and Shah S. S. H., (2015) Error correcting codes in wireless sensor networks: An energy perspective, *Applied Mathematics & Information Sciences*, vol. 9, no. 2, pp. 809–818, 2015, doi: 10.12785/amis/090229.
- [4] Arora H., Sharma D., Singh H. P., and Singh J., (2016) Bit error rate analysis of wireless sensor nodes with different packet size and distance, in *Proc. Int. Conf. Advances in Computing, Communication & Automation (ICACCA)*, 2016, doi: 10.1109/ICACCA.2016.7578864.
- [5] BenSaleh M. S., Saida R., Kacem Y. H., and Abid M., (2020) Wireless sensor network design methodologies: A survey, *Journal of Sensors*, 2020, pp. 1–13, doi: 10.1155/2020/9592836.
- [6] Faris M., Mahmud M. N., Salleh M. F. M., and Alnoor A., (2023) Wireless sensor network security: A recent review based on state-of-the-art works, *International Journal of Engineering Business Management*, vol. 15, Art. no. 18479790231157220, 2023, doi: 10.1177/18479790231157220.
- [7] Kadel R., Paudel K., Guruge D. B., and Halder S. J., (2020) Opportunities and challenges for error control schemes for wireless sensor networks: A review, *Electronics*, vol. 9, no. 3, Art. no. 504, 2020, doi: 10.3390/electronics9030504.
- [8] Kamal Z.-E.-H. and Salahuddin M. A., (2015) Introduction to wireless sensor networks, in *Wireless Sensor and Mobile Ad-Hoc Networks*, D. Benhaddou and A. Al-Fuqaha, Eds. New York, NY, USA: Springer, 2015, pp. 1–18.
- [9] Khan M. A. and Hussain S., (2020) Energy efficient direction-based topology control algorithm for WSN, *Wireless Sensor Network*, vol. 12, no. 3, pp. 37–47, 2020, doi: 10.4236/wsn.2020.123003.
- [10] Kundaeli H. N., (2020) The analysis of truncated ARQ and HARQ schemes using transition diagrams, *International Journal of Engineering, Science and Technology*, vol. 12, no. 2, pp. 35–51, 2020, doi: 10.4314/ijest.v12i2.5.
- [11] Mohamed E., Abdelkader H., Mouhib O., IdrissiAnas E. H. E., and Chakir M., (2017) Performance study of BCH error correcting codes using the bit error rate term BER, *International Journal of Engineering Research and Applications*, vol. 7, no. 2, pp. 52–54, 2017, doi: 10.9790/9622-0702025254.
- [12] Nourildean S. W., Hassib M. D., and Mohammed Y. A., (2022) Internet of things based wireless sensor network: A review, *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 27, no. 1, pp. 246–261, 2022, doi: 10.11591/ijeecs.v27.i1.pp246-261.
- [13] Onyeonwu C. C., Onuora O. N., Ajare D. C., Ozoemena C. D., and Okeke C. V., (2026) Optimization of LDPC decoding using layered Min-Sum and early stopping techniques for energy-efficient and reliable wireless sensor networks, *Research Journal in Civil, Industrial and Mechanical Engineering*, vol. 3, no. 1, pp. 16–30, 2026.
- [14] Pandey M. and Pandey V. K., (2015) Comparative performance analysis of block and convolution codes, *International Journal of Computer Applications*, vol. 119, no. 24, pp. 43–47, 2015, doi: 10.5120/21388-4398.
- [15] Patil M. and Biradar R. C., (2017) Dynamic and channel adaptive error control scheme in wireless sensor networks, *Global Journal of Computer Science and Technology: E Network, Web & Security*, vol. 17, no. E2, pp. 43–54, 2017.
- [16] Sai K., Kovi P., Jangam S., Kumar G., and Kosgi, (2017) Wireless sensor networks and applications, 2017, unpublished, doi: 10.13140/RG.2.2.23192.19207.
- [17] Spyrou E. D. and Kappatos V., (2022) Application of forward error correction (FEC) codes in wireless acoustic emission structural health monitoring on railway infrastructures, *Infrastructures*, vol. 7, no. 3, Art. no. 41, 2022, doi: 10.3390/infrastructures7030041.
- [18] Tiwari A. and Sahu V. K., (2015) Error correction channel coding practices for wireless communication systems—A review, *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 4, no. 10, pp. 151–159, 2015, doi: 10.17148/IJARCCCE.2015.41031.
- [19] Venkatesan D., Sunil B., Reddy B. A., and Naidu K. J., (2016) Low power ASIC implementation of LDPC decoder, *International Journal of Chemical Sciences*, vol. 14, no. S3, pp. 719–724, 2016.
- [20] Xu X., Tang J., and Xiang H., (2022) Data transmission reliability analysis of wireless sensor networks for social network optimization, *Journal of Sensors*, vol. 2022, Art. no. 3842722, 2022, doi: 10.1155/2022/3842722.
- [21] Yang K. and Du W., (2024) A low-density parity-check coding scheme for LoRa networking, *ACM Transactions on Sensor Networks*, vol. 20, no. 4, Art. no. 98, pp. 98:1–98:29, 2024.
- [22] Zijie F., Al-Shareeda M. A., Saare M. A., Manickam S., and Karuppayah S., (2023) Wireless sensor networks in the internet of things: Review, techniques, challenges, and future directions, *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 31, no. 2, pp. 1190–1200, 2023, doi: 10.11591/ijeecs.v31.i2.pp1190-1200.