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Investigating the Performance of Different Coding Schemes for Narrowband Internet of Things (NB-IoT) Applications

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ABSTRACT

This study investigates and compares the effectiveness of five separate coding schemes for NB–IoT applications. The coding schemes investigated were Turbo, Low Density Parity Check (LDPC), Reed Solomon (RS), Turbo–RS hybrid code and LDPC–RS hybrid code. The performance of these schemes was assessed in both Additive White Gaussian Noise (AWGN) and Rayleigh fading channel conditions using Automatic Repeat Request (ARQ) method for error detection. LDPC codes employ a (1000 × 500) parity-check matrix and belief propagation for decoding, while turbo codes utilize pseudorandom data, block interleaving, and Viterbi decoding. Reed Solomon code employs generator polynomial in encoder and syndrome decoding. The five coding schemes were modelled and simulated using MATLAB software. The effectiveness of these codes was evaluated based on the Bit Error Rate (BER), Frame Error Rate (FER), and Energy Consumption. The simulation results show that all the coding schemes exhibit high energy consumption at low SNR for both channel conditions with RS consuming the most energy. In addition, the BER exhibits 10^{-1} value while the FER is near zero at low SNR for both channel conditions. At high SNR, the BER exhibits 10^{-6} value at 1.6 dB to 2.1 dB while the FER gives 10^{-1} value at 1 dB to 1.6 dB of SNR for both channels conditions with Turbo-RS hybrid code giving the best performance. This study indicates that Turbo-RS hybrid code is ideal for ultra-reliable, energy-efficient NB-IoT systems.

Keywords: 3GPP, Narrowband Internet of Things, Error Correction Coding.

1 Introduction

The basis of any communication system relies on its signal strength, latency, and speed which work together to ensure high-quality data transmission. The quality of this process is ultimately determined by the bit error probability at the receiver, reflecting transmission accuracy. In modern systems like the Internet of Things (IoT), these factors are crucial for seamless connectivity across vast device networks. IoT has transformed global communication by interconnecting billions of devices, revolutionizing industries and daily life. Among IoT technologies, NB-IoT is designed for reliable, cost-effective, and energy-efficient communication, particularly for infrequent, small data transmissions. Its ability to function in diverse environments makes it highly dependent on fundamental communication parameters to mitigate noise, fading, and interference, ensuring reliable and energy-efficient operation [1]. Fig. 1 shows the characteristic applications of NB-IoT [2].

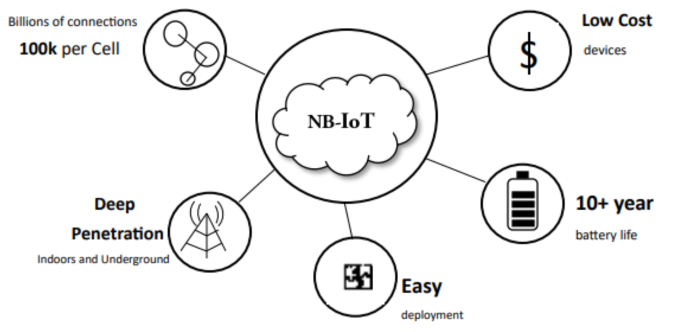

Fig. 1 NB – IoT applications.

IoT devices function in diverse environments, from dense urban areas to remote rural regions, where varying levels of noise and fading can impact communication quality. Due to the effect of noise and interference, data transmission is mostly affected by errors within the channel, which will affect the reliability of the transmitted data. Error coding schemes have been developed to identify and fix errors that might arise during transmission through the channels [3]. Unfortunately, most of these error coding schemes are computationally intensive, thereby consuming energy. For NB-IoT applications, which are resource constraints, ensuring reliable data transmission in such conditions is challenging. In these applications, there must be balance between energy efficiency and communication reliability despite fading and interferences within the channel. Error correction coding helps address these challenges in low-power networks by detecting and correcting transmission errors, thereby maintaining data integrity while minimizing energy consumption [4].

As IoT adoption expands, NB-IoT has become a critical technology for enabling long-range, low-power communication among billions of interconnected devices. However, ensuring reliable data transmission in environments affected by noise, interference, and fading presents a significant challenge. Coding schemes such as Turbo, LDPC, and Reed Solomon codes play a crucial role in mitigating errors and improving communication reliability. Many existing NB-IoT coding techniques enhance network performance by repeatedly transmitting data and control signals, extending coverage but increasing energy consumption [5], [6]. Therefore, exploring alternative forward error correction (FEC) methods that optimize both reliability and energy efficiency is essential for advancing NB-IoT technology [5], [6]. Although, individual coding schemes like Turbo and LDPC have been extensively studied in wireless communications [7], their effectiveness in NB-IoT networks and the potential benefits of hybrid coding approaches remain relatively unexplored. This research fills this gap by systematically analyzing the performance of three individual coding schemes and two hybrid

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combinations in the presence of noise and fading. Since NB-IoT operates in diverse environments, selecting an optimal coding technique or hybrid approach is essential for balancing robust data transmission with minimal power consumption. The findings of this research provide valuable insights into the most effective error correction strategies for improving NB-IoT communication while addressing power constraints in resource-limited devices.

2 Literature Review and Related Works

NB-IoT has gained significant attention due to the technology's emphasize on low-power consumption and broad coverage, making it well-suited for IoT device connectivity. As stated earlier, data transmission is impacted by noise and interference which leads to error at the receiving end. The end user device is provided with an error detection and correction scheme to combat these transmission errors. Forward Error Correction (FEC) codes, such as turbo, LDPC, and Reed Solomon codes, combined with ARQ mechanisms, have been studied to enhance reliability and efficiency in NB-IoT systems. A study by [8] compared the BER performance of turbo, LDPC, and polar codes over an AWGN channel, demonstrating that turbo codes excel at lower code rates (e.g., 1/3, 1/2) due to their near-Shannon limit performance, while LDPC codes outperform others at higher rates (e.g., 3/4, 7/8) owing to their lack of minimum distance limitations and lower error floors. However, Reed Solomon codes showed moderate performance with simpler decoding complexity. When coupled with ARQ, these codes improve throughput by retransmitting only erroneous packets, though this introduces latency trade-offs, as noted in the study.

Further research has explored the practical implementation and hardware efficiency of these coding schemes in NB-IoT contexts. For instance, Devrari *et al*. [9] analyzed the hardware performance of turbo and LDPC codes on Xilinx Virtex-5 FPGA platforms, targeting NB-IoT's machine-type communication requirements. The results indicated that LDPC codes offer lower decoding complexity and higher energy efficiency compared to turbo codes, particularly at data rates approaching 1 Gbit/s, aligning with findings from the ITU-T G.hn standard adoption in 2008, where LDPC outpaced turbo codes for similar reasons. RS code offer robust data transmission for low-data rate sensor in harsh environment. These studies collectively suggest that the choice of coding scheme in NB-IoT depends on specific application needs, such as latency tolerance, power constraints, and data rate, with hybrid ARQ-FEC approaches offering a promising compromise for optimizing performance.

2.1 Turbo Codes

Turbo codes achieve effective error correction by integrating convolutional encoding with iterative decoding. They use a pair of Recursive Systematic Convolutional (RSC) encoders with an interleaver positioned between them, which reduce correlation in the encoded sequences to enhance performance. These encoders produce a systematic output identical to the input data, along with parity bits that aid in error detection and correction. To improve transmission efficiency, selective puncturing of parity bits allows for higher code rates, such as ½ instead of the default 1/3, without significantly compromising performance [10]. A turbo encoder is made up of a pair of parallel RSC encoders, connected through a pseudo-random interleaver ensuring statistical independence between their inputs. The first encoder generates both systematic and parity bits, while the second processes an interleaved version of the input sequence, producing only parity bits. The encoded outputs are then punctured and multiplexed, maintaining a typical code rate of ½, with each encoder generating one systematic and parity bit for each input bit [11], [12]. The basic layout of the encoder's structure is in Fig. 2 [13].

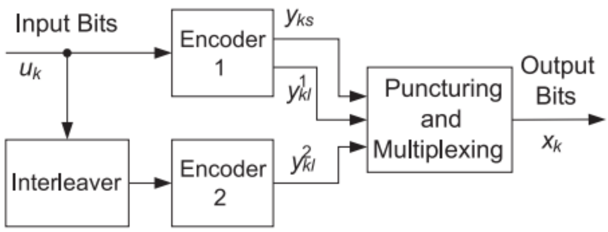

Fig. 2 Turbo encoder block.

2.2 Solomon Reed Codes

Reed-Solomon (RS) codes represent a type of error-correcting code commonly utilized in digital communications and satellite transmissions [14]. They are particularly effective at correcting burst errors involving consecutive incorrect symbols, which makes them invaluable in real-world applications where noise or damage can corrupt data. RS codes are a type of non-binary cyclic error-correcting code, invented in 1960 by Irving Reed and Gustave Solomon [15]. Unlike binary codes that operate on bits, RS codes work with symbols, where each symbol is a group of bits. These symbols are elements of a finite field called Galois Field as well, denoted as GF(q), where q is typically a power of 2 (e.g., $q=2^m$). Encoding an RS code involves transforming k message symbols into n symbols of codeword by adding $n-k$ parity symbols [16]-[18]. A generator polynomial $g(x)$ is used, which is of degree $n-k$ as in (1):

$$g(x) = (x-\alpha^b)(x-\alpha^{b+1})\cdots(x-\alpha^{b+2t-1}) \quad (1)$$

where n is the total length of the codeword, k is the number of data symbols, and t is the error correcting capability. Also, α is a primitive element of GF(2^m). The roots α^0, α^1, …, α^{n-k-1} ensure that the codeword has specific properties for error correction.

2.3 Low-Density Parity-Check Codes

Presented in 1962 by Gallager, LDPC codes are effective error-correcting codes with near-optimum performance and low decoding complexity. Once constrained by technology, they are now essential in standards like WiMAX, IEEE 802.11n, and DVB-S2 for their ability to approach channel capacity [18]-[21]. Using a parity-check matrix, LDPC decoding ensures data integrity and effectively mitigates errors in AWGN environments, and their orthogonality is represented by (2)

$$GH^T = 0 \quad (2)$$

where H^T is the transpose of H, and its multiplication with the generator matrix G result in a zero matrix of size (n-k) × k. The parity check matrix is H, and for systematic linear block code is written using (3) as:

$$H = [I_{n-k} \vdots P^T] \quad (3)$$

where the identity matrix is I_{n-k} and it is used to verify whether a codeword is valid. If

$$H \cdot X^T = 0 \quad (4)$$

where X^T is the transpose of the codeword.

A sparse parity-check matrix is employed in LDPC codes, defined in the form (N, dv, dc), where N denotes the code length, dv represents the number of ones per column, and dc per row. They are classified as regular or irregular, with $dv < dc$ ensuring a valid code rate r. Regular LDPC codes simplify analysis and require at least three ones per column for optimal performance.

The codes satisfy $H \cdot X^T = 0$, where H is the parity-check matrix, and are generated using a matrix G and message bits. Tanner graphs visually represent LDPC codes, aiding efficient decoding.

$$r = 1 - \frac{d_v}{dc} \tag{5}$$

Eq. (6) provides an illustration of a parity check matrix H along with its associated Tanner graph is in Fig. 3.

$$H = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} \tag{6}$$

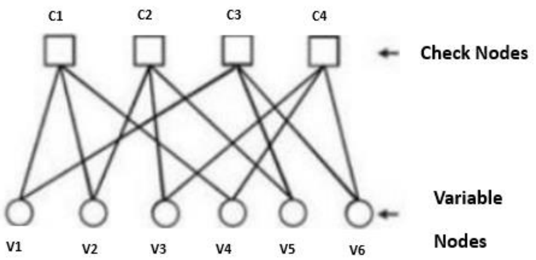

Fig. 3 Tanner graph representation.

The most commonly used method for encoding LDPC codes is Gauss-Jordan elimination. In this approach, encoding is performed by multiplying the input bits (**s**) with the generator matrix (**G**) to produce the output codeword (**c**). This process is represented in Eq. (7):

$$c = s \times G \tag{7}$$

2.4 Wireless Channel Models: AWGN and Rayleigh Fading

In the model in (8), the received signal comprises of the transmitted signal and random Gaussian noise. The signal $p(t)$ received is expressed as:

$$p(t) = x(t) + n(t) \tag{8}$$

where $p(t)$ is the signal transmitted and $n(t)$ is background noise.

The Rayleigh fading channel models multipath wireless environments without a direct line-of-sight, causing signal fluctuations due to reflection, diffraction, and scattering. It is essential for urban IoT applications, where error correction coding ensures reliable communication. This research uses a slow flat independent Rayleigh fading model to simulate multipath-induced amplitude variations [22]-[24] as expressed in Eq. (9).

$$r_t = a_t x_t + \eta_t \tag{9}$$

where a_t is a Rayleigh-distributed random variable representing the amplitude variation due to fading, and η_t is the white noise added by the channel. The envelope of the fading attenuation a_t follows a Rayleigh distribution, and its statistical model is described by its probability density function, given in (10).

$$p(a) = \begin{cases} \frac{a}{\sigma^2} exp\left(-\frac{a^2}{2\sigma^2}\right), a \geq 0 \\ 0, \qquad\qquad\qquad a < 0 \end{cases} \tag{10}$$

2.5 Review of Related Studies

Zhang *et al*. [25] evaluate error correction coding schemes, including RS and Turbo codes, in NB-IoT, focusing on energy efficiency. The authors introduce a novel coding approach that optimizes energy usage by leveraging adaptive coding rates and low-complexity decoding algorithms, achieving significant energy savings while maintaining reliable data transmission. It provides insights into trade-offs between coding complexity and power consumption. The results show that RS codes offer better energy efficiency for short messages, while Turbo codes excel in high-noise environments but consume more power due to iterative decoding. While Chen et. al [26] proposes an optimized RS decoding algorithm for IoT devices, analyzing its BER and energy consumption. While not specific to NB-IoT, the low-power focus is applicable to Turbo-RS and LDPC-RS hybrids. LDPC and RS codes were investigated for NB-IoT systems integrated with Power Line Communications (PLC) in [27]. The authors focus on LDPC codes in NB-IoT, simulating their BER and FER performance under AWGN conditions using BPSK modulation. By simulating various rate parameters and block sizes, the authors assess how these parameters influence the bit-level and frame-level error rates, providing insights into trade-offs between coding efficiency and robustness against noise. Their findings highlight that LDPC codes can achieve strong error correction performance in NB-IoT, particularly when optimized for specific channel conditions. LDPC codes outperform RS at high SNR, but RS is more energy-efficient for short code lengths. This study provides a baseline for comparing LDPC and LDPC-RS hybrids in this research.

Turbo codes in low-power IoT contexts, including NB-IoT-like systems, with detailed simulations of BER and energy consumption was examined by Vivier et. al [28]. The authors focus on enhancing the performance of turbo codes, to suit the stringent energy constraints of IoT applications. Modifications proposition to the turbo coding framework, including adaptive interleaver designs and simplified decoding algorithms were made, to reduce computational complexity and power consumption while maintaining high error correction efficiency. The study demonstrates that these optimized turbo codes achieve significant energy savings compared to conventional turbo coding schemes, and is useful for Turbo and Turbo-RS modeling in this research. Turbo and LDPC codes in NB-IoT were analyzed, with simulation of energy consumption in [29]. The results highlight that certain configuration of LDPC codes offer lower energy consumption but may introduce higher latency, while turbo codes can reduce latency at the cost of increased power demands. The methodology and metrics are applicable to hybrid schemes and energy analysis of this research.

An efficient implementation of LDPC encoding on microcontroller-based IoT devices was presented in [30]. The approach leverages the Quasi-Cyclic (QC) variant of LDPC codes and decomposes the classic Richardson–Urbanke algorithm into cyclic shifts and simple GF (2) instructions, aligning with the CPU operations of resource-constrained devices. It demonstrates that LDPC codes can be effectively utilized in systems with constrained computational resources, achieving reduced energy usage and improved error resilience compared to traditional block codes like RS and BCH. The research study in [31] introduces an Adaptive Iterative Decoding (AID) methodology using LDPC codes in Wireless Body Area Networks (WBANs). By reducing the number of decoding iterations while maintaining a desired BER, the scheme achieves a 20–25% reduction in total energy consumption, addressing the critical challenge of energy efficiency in WBANs.

3 Methodology

The model of the NB-IoT communication system includes a transmitter, a receiver, and a channel, with data encoded using Turbo, RS, LDPC codes coupled with ARQ error detection on the receiving end. The signal undergoes QPSK modulation and transmitted via either an AWGN or Rayleigh fading channel, representing typical wireless environments. At the receiver, the signal is demodulated and decoded, and system performance is assessed. The simulations were performed in MATLAB environment.

3.1 The three different coding schemes model

The three different coding schemes are: Turbo, LDPC, and RS codes.

(i) LDPC Code Model: An (N, K) LDPC code with a 1000 × 500 parity-check matrix encodes data by multiplying the message vector with the matrix. The encoded data undergoes QPSK modulation and is propagated through AWGN and Rayleigh fading channels. At the receiver, the belief propagation algorithm corrects errors using Tanner graphs [32].

(ii) Turbo Code Model: Random binary data is generated and encoded using a Turbo encoder. After interleaving and QPSK modulation, the signal is transmitted through AWGN and Rayleigh fading channels. At the receiver, coherent demodulation and Viterbi decoding ensure accurate data reconstruction. The encoded data undergoes QPSK modulation and is transmitted over AWGN and Rayleigh fading channels, following the mathematical models in (11) and (12).

$$f(x) = \frac{1}{\sqrt{2\pi N}} exp\left(\frac{-x^2}{2N}\right) \tag{11}$$

$$p(r) = \frac{r}{\sigma^2} exp\left(-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2\right) \tag{12}$$

where N is average noise power, σ represents the rms amplitude of the received signal, $r^2/2$ denotes the power at a given instance, σ^2 refers to locally averaged power of the received signal prior to detection.

The Eqs. (11) and (12) applies to LDPC code as well, as they are of the same category as block code..

$$y_j = \sum_{i=0}^{m} g_{Ji} u_{t-1} \tag{13}$$

where u_t is the input bit at time t, g_{ji} are the generator polynomials, and y_j is the encoded output. Eq. (13) also models convolutional class of code which includes turbo code.

(iii) RS Code Model: RS codes are typically defined as (n, k, t), with n representing the length of the codeword and k that of the message and then t = (n – k)/2, is the error correcting capability. It operates over GF (2^8) for an 8-bit symbols, and uses QPSK modulation for both channel conditions and a syndrome decoding.

Table 1 presents the simulation parameters used in this study to simulate and evaluate the performance metrics, such as BER, FER, and energy consumption.

Table 1: Simulation parameters of the three coding schemes

Parameters	**Turbo code**	**LDPC code**	**RS code**
Modulation	QPSK	QPSK	QPSK
Interleaver type	UMTS	Nil	Nil
No of iterations	8	50	Nil
Decoding Techniques	Log-MAP Algorithm	Belief Propagation (BP)	Syndrome Decoding
Code Lengths	1024	1024	255 symbols
Code Rate	1/3	½	0.87
Channels	AWGN, Rayleigh fading	AWGN, Rayleigh fading	AWGN and Rayleigh fading

3.2 Hybridizing two-coding scheme of the same class

In this study, two coding schemes were hybridized to assess the performance over both AWGN and Rayleigh fading channel conditions for NB-IoT. The hybridized coding schemes were

(i) Turbo-RS hybridized codes: Fig. 4 shows the block diagram of the Turbo- RS code, which involves the integration of turbo and RS codes.

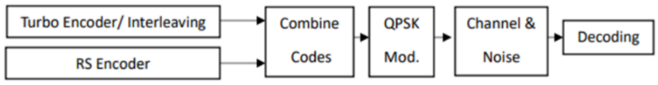

Fig. 4 Turbo –RS hybridized codes.

The hybridized approach entails designing a generator polynomial to encode the RS code and turbo encoder for turbo code which composed of two parallel convolutional encoders separated by an interleaver. The input bits are first processed by an interleaver prior to encoding by the second encoder, the interleaver ensures diversity of the encoded bits. After which the codes are combined, and modulated using QPSK for transmission. Noise is introduced into the channel, AWGN and Rayleigh fading. Then, the log-MAP decoder is used to decode the received signal [33].

(ii) LDPC-RS hybridized codes: Fig. 5 presents the block diagram of LDPC- RS code, which involves the integration of LDPC and RS codes.

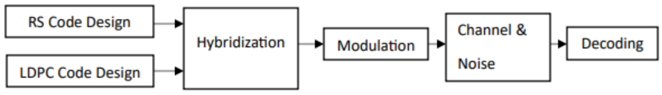

Fig. 5 LDPC - RS hybridized codes.

As shown in Fig. 5, and a defined LDPC code using a (1000 x 500) parity-check matrix. The LDPC code usually operates on large sparse matrices and has strong error-correction capabilities. In order to hybridize, the encoded RS code is combined with LDPC. Then, QPSK modulation is used for transmission and noise (AWGN or Rayleigh fading) is introduced to the channel. The log-MAP decoder is used to decode the received signal.

3.3 Performance evaluation of all the coding schemes

The performance of the five coding schemes was evaluated based on the BER, FER, and energy consumption.

(i) BER: This represents the ratio between incorrectly received bits relative to the total number of bits transmitted. It means the percentage of bits received with errors. This was estimated using

$$BER = \frac{N_{error}}{N_{total}} \tag{14}$$

where *Nerror* represents the bits count in error, *Ntotal* denotes the total number of bits.

(ii) FER: This is a metric employed to assess the quality of communication in digital system. FER is the ratio of incorrectly received frames to the overall number of transmitted frames. This implies the percentage of frames that have been received with errors. The FER was estimated using

$$FER = \frac{N_e}{N_t} \tag{15}$$

where N_e is the number of erroneous frames (frames with one or more-bit errors), N_t represents the total count of transmitted frames.

(iii) Energy Consumption: This is a critical metric in NB-IoT, where devices are often battery-powered. The energy required for data transmission is modelled as:

$$E_{trans} = P_{tx} \times T_{trans} \quad (16)$$

where P_{tx} denotes the transmission power, and T_{trans} represents the duration of transmission.

The overall power consumption, considering both transmission and reception is expressed by (17).

$$E_{total} = E_{Trans} + E_{Rx} = \frac{M}{B}(P_{Tx} + p_{Rx}) \times P_{st} \quad (17)$$

where, P_{Tx} represents the power used for transmission, P_{Rx} denotes the power used for reception, M refers to the uplink packet size expressed in bits, B indicates the bit rate of transmission, P_{st} indicates the success probability of transmission.

Modelling and simulations were conducted in MATLAB environment on an *hp* laptop with 64-bit operating system and an installed RAM of 8GB, with processor of Intel(R) Core *i*5.

4 Results and Discussions

The results of simulations are presented here, evaluating various coding schemes for NB-IoT applications under both AWGN and Rayleigh fading channel conditions.

4.1 Performance over an AWGN Channel

Fig. 6 presents the BER performance across the five coding schemes over an AWGN channel in relation to the Signal-to-Noise Ratio (SNR). In low SNR region typically between 0 and 0.2 dB, the overall performance of the five coding schemes is similar, all exhibiting high BERs. This reflects the inherent difficulty in decoding signals under very low SNR conditions. At SNR Region (1.1 dB and above) the five coding schemes exhibits an acceptable BER of 10^{-5} value. The turbo–RS code exhibits the best performance at 1.1 dB, with LDPC–RS code close to the same SNR value. Turbo code followed in performance, then LDPC code. while RS code exhibits the poorest performance attaining almost 1.2 dB of SNR. It was observed that turbo-RS hybridized code exhibits the best performance across the SNR range with 31.3% BER improvement over RS code at 1.1 dB of SNR. The hybrid codes performed excellent because of the competitive advantage of two codes, while turbo code performs well because of its iterative decoding capabilities. RS code performs poorest due to their simplicity and lack of robust performance to noise.

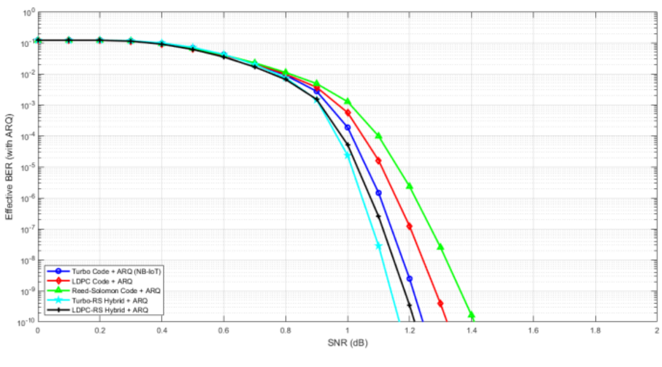

Fig. 6 BER performance plot of the five coding scheme under AWGN channel using ARQ.

Fig. 7 presents the BER performance across the five coding schemes over an AWGN channel as a function of SNR. At low SNR region between 0 and 0.2 dB, all coding schemes exhibit high FERs close to unity due to limited decoding capability in noise-dominant conditions. Beyond this point, the performance of these coding schemes becomes significant. At SNR region (1.1 – 1.3 dB) the five coding schemes exhibits an acceptable FER of 10^{-1} value for an ARQ coupled codes. Turbo code achieved target FER at 1.08 dB, followed by turbo-RS hybrid and LDPC codes. LDPC-RS hybrid code exhibits target FER at closely higher SNR, while RS code exhibit target FER at the highest SNR of 1.22 dB. It was observed that turbo code and its hybrid performed well exhibiting about 30% performance improvement because of its iterative decoding ability, while LDPC-RS hybrid code performs better than RS code because LDPC possess strong error correction capabilities. RS code performs the poorest due to its lack of robust performance to noise.

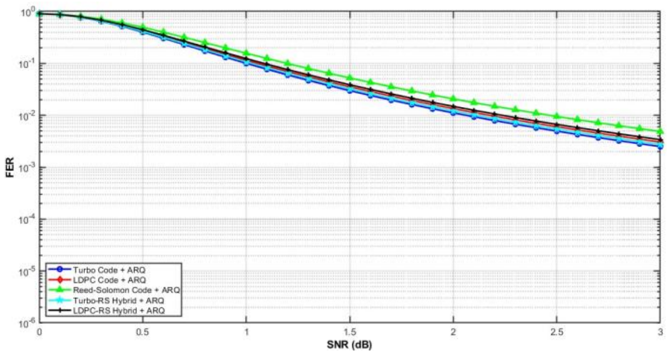

Fig. 7 FER performance of the five coding scheme over AWGN channel using ARQ.

Fig. 8 shows the energy consumption performance of five coding schemes over an AWGN channel as a function of SNR. At very low SNR, all the coding schemes exhibit high energy consumption due to increased decoding complexity in noise-dominated conditions. As the SNR increases beyond this point, the energy consumed by these coding schemes reduces gradually and almost constant at high SNR (3.5 – 4 dB) as shown in Fig. 8. For all the SNR values, Turbo code has the least energy consumption followed by turbo –RS code while RS code consumes the most energy. Thereafter, the Turbo code has the best performance followed by the Turbo–RS code. It can be deduced that considering the BER and FER performance of the Turbo- RS code, it is adjudged as the best performing codes and an ideal candidate for NB-IoT applications.

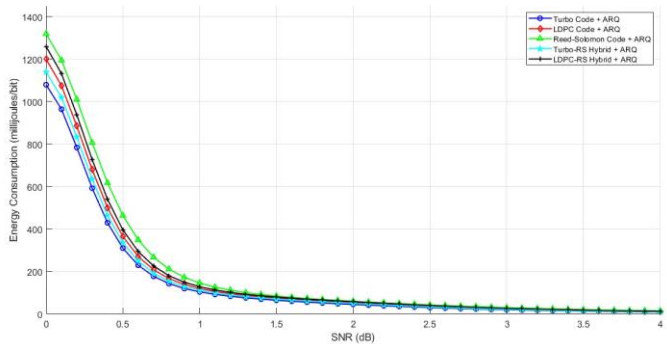

Fig. 8 Energy consumption performance of the five coding scheme over AWGN channel.

4.2 Performance in the presence of Rayleigh Fading Channel

Fig. 9 represents the BER operation of five coding schemes in a Rayleigh fading channel as a relation to SNR. In low SNR region between 0–0.2 dB, all the five coding schemes are similar. The scheme all exhibits high BER. As the SNR increases beyond 0.2 dB, the individual performances of these schemes become noticeable. In the SNR region (1 – 1.5 dB) Turbo-RS hybrid code achieves target BER of 10^{-5} value, followed by LDPC–RS hybrid code. Turbo and LDPC codes followed closely, while RS code exhibit high SNR values to achieve target BER. The hybrid codes perform better in Rayleigh fading channel, especially beyond 1 dB of SNR. As the SNR increases, so does the hybridized codes outperform single codes in a fading channel utilizing the competitive advantage of two codes to overcome fading challenges better. The Turbo -RS code has 30% performance improvement over RS code at 1.5dB of SNR.

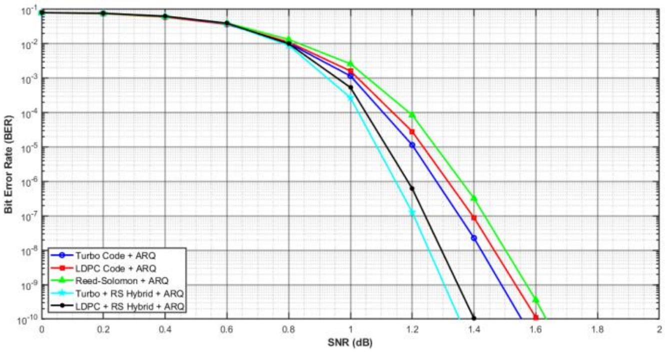

Fig. 9 BER plot of five schemes of codes under Rayleigh fading channel.

Fig. 10 represents the FER performance of five coding schemes under a Rayleigh fading channel in relation to SNR. At low SNR region between 0 and 0.2 dB, all coding schemes exhibit high FERs close to unity due to limited decoding capability in noise-dominant conditions. At SNR region (1.2–1.5 dB), Turbo Code achieved target FER at 1.2 dB, while LDPC, Turbo-RS hybrid, LDPC-RS hybrid, and RS codes followed closely. While RS code provides error protection based on fixed-length blocks, but their performance under fading conditions is less robust. However, turbo code exhibits the best performance due to its iterative decoding nature with 31% performance improvement over RS code.

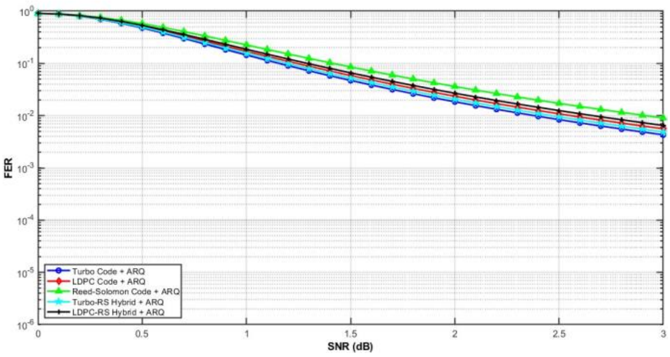

Fig. 10 FER performance plot of the five coding scheme under Rayleigh fading channel.

Fig. 11 shows the energy consumption performance of five coding schemes under a Rayleigh fading channel in relation to SNR using ARQ. In the low SNR region, all the coding schemes exhibit high energy consumption due to increased decoding complexity in noise dominated conditions. As the SNR increases beyond this point, the energy consumed by these coding schemes reduces gradually and almost constant at high SNR (3.5 – 4 dB) as shown in Fig. 11. For all the SNR values, Turbo code has the least energy consumption followed by turbo – RS code while RS code consumes the most energy. Thereafter, the Turbo code has the best performance followed by the Turbo–RS code. It can be deduced that considering the BER and FER performance of the Turbo- RS code, it is adjudged as the best performing codes and an ideal candidate for NB-IoT applications.

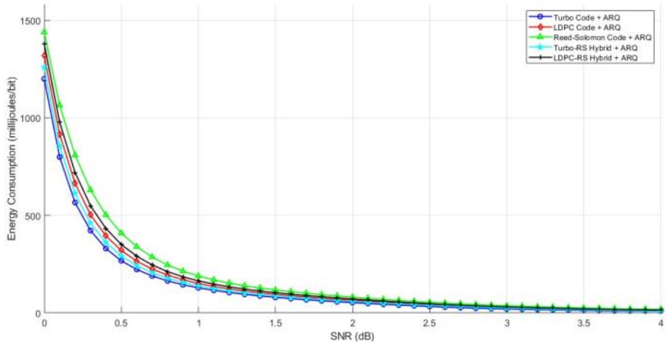

Fig. 11 Energy consumption of the five coding schemes under Rayleigh fading channel.

5 Conclusions

This study investigates the performance of five coding schemes for NB-IoT applications. The five coding schemes was modelled and simulated in MATLAB environment considering both AWGN and Rayleigh fading channel conditions. To achieve the requirements of NB-IoT applications, ARQ mechanism was used with the code, with maximum retransmission set at three to minimize power consumption. This study shows that the Turbo-RS hybrid codes are robust to severe noise condition in NB-IoT applications, utilizing the competitive advantage of two codes. The integration of ARQ mechanisms further bolsters performance by enabling retransmission of erroneous data, thereby reducing packet loss in simulated noisy environments.

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Author Contributions

J. K. Afuye: Investigation, Formal Analysis, Writing - original draft; **B. C. Ubochi:** Supervision, Formal Analysis, Writing – Reviewing and Editing; **K. B. Adedeji:** Conceptualization, Supervision, Formal Analysis, Writing – Reviewing and Editing.

Conflict of Interest

The authors declare no competing financial or non-financial interests, nor any personal relationships, that could influence the work reported herein.

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Generative AI Statement

No generative AI/LLM was used in any stage of this manuscript.

Data Availability

Data will be made available on request.

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