

Bit error rate analysis of various error correction codes with concatenated RS-convolutional codes

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Abstract

This rapid expansion has driven the development and adoption of a wide variety of communication standards, creating a critical need for systems that are both robust and adaptable. One innovative solution lies in the design of intelligent receivers capable of autonomously identifying and adapting to transmitter parameters based solely on the received signal characteristics. Among the key elements in ensuring the reliability and efficiency of such systems is channel coding, which introduces redundancy into transmitted data to detect and correct errors caused by noise, interference, or signal degradation during transmission. One effective method is code concatenation, which involves the sequential or parallel integration of two or more coding schemes. This article examines the performance of a sequential concatenated coding approach that integrates Reed-Solomon (RS) codes as the outer code with convolutional codes as the inner code. RS codes are highly effective in correcting burst errors, while convolutional codes excel at correcting random errors. When used in combination, these codes complement each other, resulting in improved error correction capabilities. The article evaluates this hybrid approach by analyzing the bit error rate (BER) under varying signal-to-noise ratio (SNR) conditions, demonstrating that the concatenated scheme consistently outperforms individual coding strategies such as RS, convolutional, or LDPC codes alone in noisy communication environments.

Subject Classification: 94B05, 94B60.

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1. Introduction

Digital techniques are on our doorstep, their use is expanding and affecting the fields of sound, video and data. There are no more dedicated media, the

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routing of sound, video and data in general is done by borrowing various mediums. The unpredictability of the message sent by the source then requires the receiver to use techniques allowing him to verify both the accuracy and the certainty of the information received [1].

Along with the investigation of new protocols in the network layer, solutions applied to the physical layer are sought. In this context, the techniques already used for wireless communications are envisaged for application to optics [2].

Among these techniques, we are interested in error correcting coding [3], in order to improve the performance of optical transmissions. In the context of future optical networks, performance in terms of error rate must be as low as possible (10^{-9} to 10^{-12}), while ensuring high speeds [4]. However, in this context, the imperfections of the optoelectronic components introduce many limitations on the performance [5]. This is why the error-correcting coding techniques, or channel coding, which have already proved their worth in the wireless domain, are being considered for optics.

In order to reduce the error rate in the message, symbols are added to the message according to a law known to both the sender and the receiver. Two types of techniques exist:

- i. A technique that only determines whether the received message is error-prone.
- ii. A technique which makes it possible to detect and correct.

2. Literature survey

Free-space optical communication (FSO) systems are capable of supporting high data rates and are often used for the transmission of audio, video, and digital data. FSO has become an attractive solution for last-mile connectivity, disaster recovery, and temporary network installations. In optical fiber communication, controlling the bit error rate (BER) and ensuring low latency are critical requirements, as highlighted in [6][7]. Several recent studies have considered replacing the Reed-Solomon codes, already standardized for transoceanic communications, with new codes, more efficient and less redundant, such as low-density codes (LDPC: Low-Density Parity Check) [8] [9].

The Reed-Solomon codes are error-correcting detector codes capable of correcting independent errors, and contiguous erroneous symbols in so far as the number of errors does not exceed the ability to correct. Decoding apart from error detection requires a computation unit operating on the Galois field [10] [11].

Paper introduces the codes which approach the Shannon limit and which have the best performance in a context such as LDPC codes (low-density parity-check code), and RS codes (Reed-Solomon code) [12], convolutional codes [13] [14] and concatenated Reed Solomon-convolutional codes [15] [16]. In this paper, the performance of the DVB-T2-Lite system using the technique termed as spatial diversity in different channel scenarios was addressed [22]. In this

paper, the design of error correction codes with AI techniques was proposed [23]. This paper addresses the issue of using high-density algorithms in a distributed computer system where emerging processors are present. In order to minimize the impact of stragglers, it has previously been suggested that data be encrypted with the code to clear and decrypt the primary server at the end of the calculation [24]. This article introduced a cognitive radio-based cross-layer resource allocation framework for video streaming over distributed networks using multi-carrier DS-CDMA modulation with frequency-selective fading channels [25]. Foundational Aspects of Convolutional Codes were elaborated in this article [26]. A proposed low-latency coding scheme called Semi-Random Block-Oriented Convolution Code (SRBO-CC) is similar to Block Markov Superposition Transmission (BMST) [30]. This paper addresses the fundamental problem of cutting 5G transport networks, namely, the reliable VN embedding with dedicated EON protection [32]. To minimize the overuse of a dedicated security app, use the bandwidth congestion and the V-Link requirement for separation between multiple modes while using the flexibility capabilities provided by EON. This paper provides a deep and clear understanding of the Reed-Solomon codes and Convolutional codes that make it simple and easy to understand and use [34].

3. Proposed Methodology

3.1. OFDM Transmission System Without Encoding

In an OFDM transmission system, as shown in Figure 1, the bits to be transmitted are allocated to N subchannels and are mapped into complex modulation symbols. These complex values together with their symmetrical conjugate are then sent to the IFFT operation, forming $2N$ values. The resulting vector is converted into a continuous-time signal through a digital to analog (D/A) converter to be transmitted over the channel. During transmission, this signal will be subject to noise, which will cause system errors.

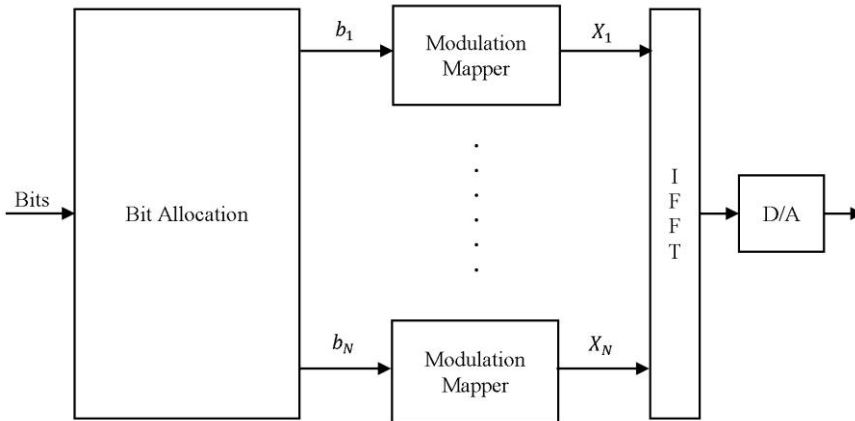


Figure 1
OFDM transmission system without coding

Figure 2 shows the block diagram of reception. After analog-to-digital (A/D) conversion, the received signal reaches the FFT operator, giving Y_i complex values. Then, the resulting signal is converted into bits by the modulation demapper which are the inputs to a parallel-serial converter.

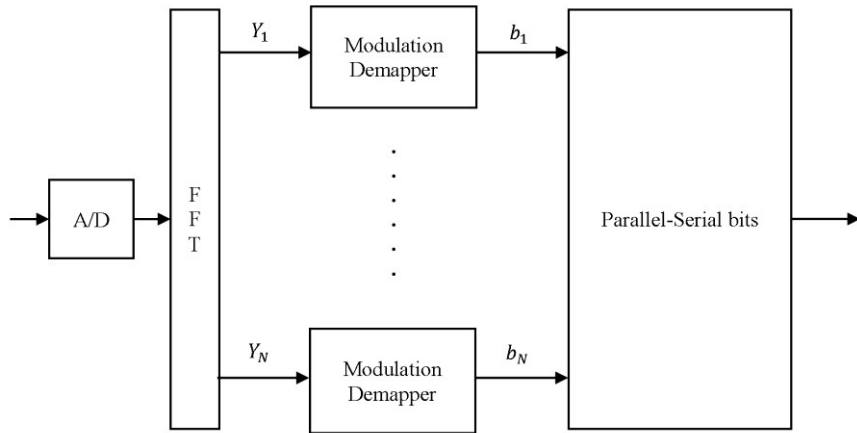


Figure 2
OFDM reception system without coding

However, utilization of error correction codes in transmission system, the information bits pass through the encoder and are allocated into various subchannels. While on reception, the FFT operation is performed and the modulation symbols are demapped. The bits in each subchannel go through a parallel-serial converter and reach the decoder.

Followings are the various error correction codes proposed in this paper.

A. Low Density Parity Check Coding (LDPC)

Low-Density Parity Check (LDPC) is a type of linear block code initially proposed in 1962 by Robert Gallager [17]. Consequently, by his time it was almost impossible to demonstrate the performance of the LDPC-Gallager encoding regarding the performance in terms of BER and the approach to the limit Shannon [18].

In other work, irregular LDPC codes have been used in simulations, reaching 0.046dB at the Shannon limit with BER 10^{-6} [19]. LDPC is currently applied in different telecommunications standards such as: IEEE 802.16 (Mobile WiMAX) [20], IEEE 802.11n (WIFI) [21], IEEE 802.20, IEEE 802.3 and in DVB-S2X, DVB-T2-Lite [22], with codeword lengths from 384 bits for wireless standards to 64800 bits for terrestrial digital television standards [22] and other optional ones for IEEE 802.11ad (WiGig), IEEE 802.11 ac (WiFi), among others. The performance of LDPC makes it attractive in applications that require high transmission rates [23].

The main characteristic that differentiates a block code from LDPC is the decoding. While the first uses Maximum Likelihood (ML) algorithms, or syndrome decoders, the second generally uses linear programming (LP) and iterative algorithms e.g., belief-propagation (BPA) or message-passing (MPA), product-sum (SPA), or min-sum (MSA). All of them based on Hard-decision and soft-decision decoding [24].

During LDPC code creation, the generator matrix ($k \times n$) maps the message vector " u ", $u \in F_2^k$ into a codeword $c \in F_2^n$ of length n at a rate $R = k/n$ [25]. Generally, the creation of the generating matrix " G ". It starts from the parity check matrix " H ", where the condition of equation (1) must be fulfilled.

$$HG^T = 0 \quad (1)$$

There are two ways to represent LDPC codes: through linear matrices or graphically (Tanner).

The parity check matrix of equation (2) has a number of rows n and a number of columns m defined by $(n \times m)$.

$$H = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

For the parity matrix to be of low density, it must have an amount of 1's per row and per column, named as W_r and W_c , correspondingly, that fulfill the condition of: $W_c \ll n$ and $W_r \ll m$ [25]. A graphical representation of the matrix " H ", from Equation 2, can be seen in Figure 3.

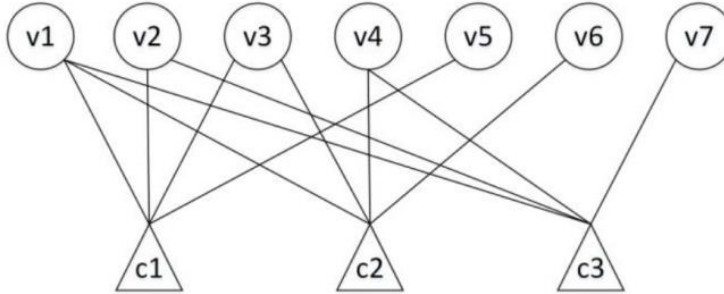


Figure 3

Graphical representation of the parity check matrix H for an LDPC code [24]

In this representation, the triangle symbolizes the parity nodes, and their number corresponds to the number of bits participating in the parity equation. During decoding, the parity check operations are represented by exchanges via these links between the variable nodes and those of parity.

The encoding and decoding scheme using an iterative algorithm can be represented in a general way as in Figure 4.

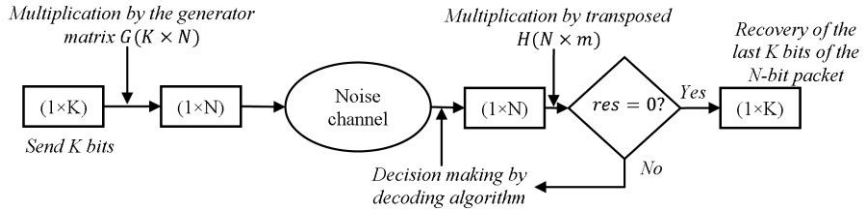


Figure 4
Transmission chain with LDPC coding / decoding

The transmitter comprises a coding block which carries out the multiplication of the useful data with the generator matrix. This encoding operation does not a priori pose any particular constraints except the fact of working on data packets of fixed size imposed by K (or N).

At the receiver, an iterative algorithm whose role is to determine the most probable sequence, is implemented. A decision is taken on the bits making up the received word and a test is carried out at each iteration to verify whether the decided word is a code word or not. This operation is carried out by multiplying the word decided with the matrix H transposed so as to verify the parity equation. As long as the decided word is not a code word and as long as the maximum number of iterations is not reached, the iterations continue.

B. Convolutional Codes

Two main families of ECC (error correcting codes) are to be distinguished: convolutional codes and block codes. By definition, convolutional codes calculate redundancy continuously as the data stream arrives while block codes generate redundancy by data blocks. It is said to be systematic if the useful information bits are found in the coded word C . This is reflected in the matrix representation. This representation is called the systematic form of the generator matrix.

Convolutional codes were initially invented in 1954 by Elias [26]. The principle of convolutional codes is to consider the message to be sent as a semi-infinite sequence of symbols. It consists in passing the useful message to be encoded in a succession of shift registers. There are 3 parameters of the convolutional codes: K (useful information bits), B (the number of code shift registers), N (coded bits after the encoder). One also defines the length of constraint of the code which is equal to: $B + 1$. For a convolutional encoder illustrated in Figure 5, a coding scheme of efficiency R equal to 0.5 is most often used. We can illustrate on a fairly simple example the main differences between the two types of code. Let us take the example of a convolutional code NSC [27] [28], we can write the generator polynomials of this code in the form:

$$G = [1 + D + D^2, 1 + D^2] \quad (3)$$

Two versions of the equivalent RSC encoder can be obtained as follows:

First version:

$$G_1 = [1 + D + D^2, 1 + D^2] \quad (4)$$

Second version:

$$G_2 = (1 + D + D^2) \left[1, \frac{1+D^2}{1+D+D^2} \right] \quad (5)$$

Even if the performances between NSC codes and RSC codes are very similar, it is shown in [29] that a systematic recursive encoder has better performances at low SNRs than a non-systematic convolutional code, however the differences are minimal.

C. Reed-Solomon Codes

RS codes are effective codes that have been around for years, they are already applied for standardized long distance systems (ITU-G975 and ITU-G709) [31]. To evaluate the performance of the studied codes, we will use as criterion the coding gain (NCG: Net Coding Gain). In fact, to increase the coding gain, two solutions are possible: either we increase the SNR, or we decrease the useful bit rate by concatenating several encoders [32], for example, RS (239,223) + RS (255,239).

The Reed-Solomon codes (non-binary) are obtained by extension of the BCH codes (binary), the binary symbols of the BCH codes are transformed into m-array symbols to obtain the RS codes. They are based on Galois field theory [33], in fact RS codes are based on $GF(2^m | m \geq 3)$ and BCH codes on $GF(2)$. Moreover, they are all cyclic linear codes. RS codes are always written in the form (N, K) where N is related to the class of the code: $N = 2^m - 1$. The maximum number of correctable errors is expressed by t or $2t = N - K$.

1. RS Codes Encoding

RS codes are block codes, so if we express them with a generator matrix in polynomial form (G), we get:

$$G(x) = (x - \alpha)(x - \alpha^2), \dots, (x - \alpha^{N-K}) \quad (6)$$

Where α is a primitive root of the field $GF(2^m)$.

R being defined as the remainder of the Euclidean division of the quantity: $message \times X^{2t}$ by G , we can write:

$$C = message \times X^{2t} + R \quad (7)$$

So the property for this code word is to cancel out for $X = \alpha^i$ with $1 \leq i \leq \alpha$.

2. Decoding RS codes

The most widely used algorithm for RS decoding is the Berlekamp-Massey algorithm [33]. It is based on hard decisions. The decoding algorithm is applied if the code syndrome is not zero. The principle is to find among all the valid code words the one which is at the smallest distance from the detected erroneous word. Indeed, this algorithm proceeds in four steps (Figure 5):

- Calculation of the syndrome by taking $X = \alpha^i$.

- Calculation of error localization polynomials and amplitude.
- Calculation of the roots and evaluation of the two polynomials.
- Summation of the constituted polynomial and the received polynomial to reconstruct the starting information without error.

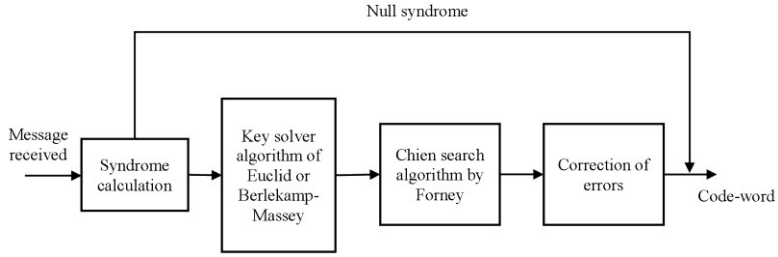


Figure 5
RS decoding scheme

3. Performance

RS codes are linear, non-iterative, and cyclic codes. The result can be obtained by simulation or by mathematical calculations.

For each bit, if we define the probability of correctable error P_{ce} :

$$P_{symbol} = 1 - (1 - P_{ce})^m \quad (8)$$

So the probability of non-detection P_{endc} per symbol is determined by:

$$P_{endc} = \sum_{i=1}^N A_i P_{symbol}^i (1 - P_{symbol})^{N-i} \quad (9)$$

Where

$$\begin{cases} A_0 = 1 \\ A_j = 0, \text{ when } 1 \leq j \leq N - K \\ A_j = \binom{N}{j} \sum_{h=0}^{j-1-(N-K)} (-1)^h \binom{j}{h} [(N+1)^{j-h-(N-K)} - 1], \text{ when } (N-K) + 1 \leq j \leq N \end{cases}$$

The probability of symbol error P_{se} for the decoding is expressed as:

$$P_{se} \leq \sum_{i=t+1}^N \binom{N}{i} P_{symbol}^i (1 - P_{ce})^{N-i} \quad (10)$$

So the total probability of error per symbol is written:

$$P_{total} = P_{endc} + P_{se} \cong P_{se} = \frac{1}{N} \sum_{j=t+1}^N j \binom{N}{j} P_{symbol}^j (1 - P_{ce})^{N-j} \quad (11)$$

If an approximation is made:

$$P_{total} = \frac{t+1}{N} \binom{N}{t+1} P_{symbol}^{t+1} (1 - P_{ce})^{N-t-1} \quad (12)$$

D. Concatenation of Reed-Solomon Codes with Convolutional Codes

Convolutional codes do not perform at the desired level in case of error bursts (consecutive incorrect bits). As a result of the efforts to eliminate this disadvantage, a new coding technique called sequential code was designed by

David Forney in 1966. Convolutional codes using soft-predictive decoder at low signal-to-noise ratio have better performance than Reed-Solomon codes of the same complexity [35]. Considering these situations, Forney created the serial sequential code block diagram in Figure 6 by using the convolutional code and the Reed-Solomon code consecutively.

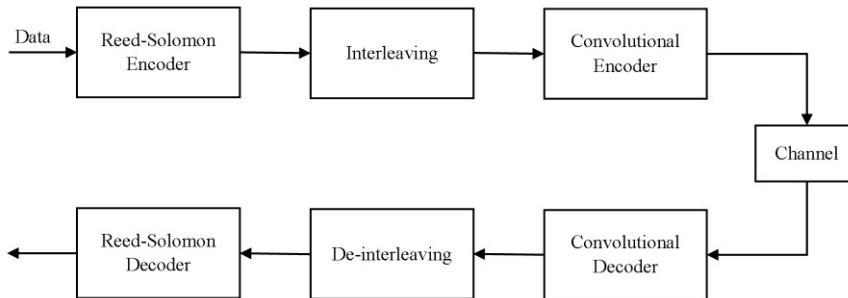


Figure 6
Concatenation of Reed-Solomon and Convolutional codes

4. Results and Discussions

Simulation results are cited below for Concatenation of Reed-Solomon Codes with Convolutional Codes.

Figure 7 presents a simulation result for IEEE 802.16a, illustrating the Bit Error Rate (BER) performance against the Signal-to-Noise Ratio (SNR) for different modulation and coding schemes. The x-axis represents the SNR, while the y-axis represents the BER on a logarithmic scale.

Three curves are plotted:

- i. **Blue (bask-1/2):** This represents Binary Amplitude Shift Keying (BASK) with a 1/2 coding rate. The curve shows better performance at lower SNR values.
- ii. **Green (qpsk-1/2):** Quadrature Phase Shift Keying (QPSK) with a 1/2 coding rate. It provides improved BER performance compared to BASK-1/2.
- iii. **Red (qpsk-3/4):** QPSK with a 3/4 coding rate, which offers higher spectral efficiency but results in a slightly higher BER at lower SNRs.

From the graph, it is evident that higher SNR values lead to lower BER, indicating improved system performance. QPSK with a lower coding rate (1/2) performs better than QPSK-3/4 at lower SNRs but sacrifices data rate. The results highlight the trade-off between robustness and spectral efficiency in IEEE 802.16a.

This analysis is critical for optimizing modulation and coding schemes in wireless communication systems to achieve the desired reliability and efficiency.

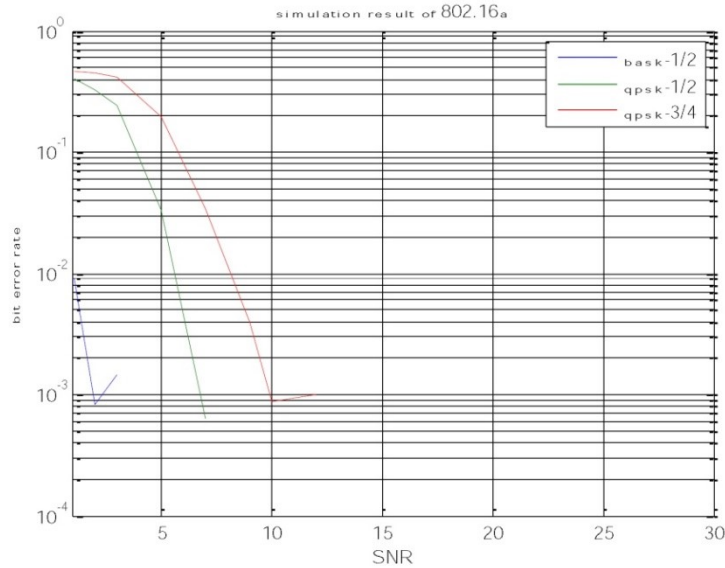


Figure 7
BER performance for concatenated Convolutional codes

The provided graph illustrates the Bit Error Rate (BER) performance versus Signal-to-Noise Ratio (SNR) for different modulation schemes in IEEE 802.16a systems. The x-axis represents SNR, while the y-axis (logarithmic scale) denotes BER. The simulation compares BASK-1/2, QPSK-1/2, and QPSK-3/4 modulation schemes.

From the results, BASK-1/2 (blue curve) exhibits the lowest BER at lower SNRs, making it more resilient to noise but less efficient in data transmission. QPSK-1/2 (green curve) improves spectral efficiency while maintaining a lower BER compared to QPSK-3/4 (red curve), which has a higher coding rate but requires a higher SNR to achieve acceptable performance.

Table 1
BER at various SNR values for Convolutional codes

SNR	Bit Error Rate		
	BPSK-1/2	QPSK-1/2	QPSK-3/4
0	0.0091	0.4009	0.4618
2	0.0008	0.3312	0.4466
4	0.0014	0.2443	0.4152
6	0	0.0335	0.1986
8	0	0.0006	0.0337
10	0	0	0.0039
12	0	0	0.0008
14	0	0	0.0010

Table 1 confirms this trend, showing that at $\text{SNR} = 6$ dB, QPSK-1/2 achieves a BER of 0.0335, while QPSK-3/4 has a higher BER of 0.1986. As SNR increases, BER decreases significantly, reaching near-zero values at $\text{SNR} \geq 10$ dB.

The graph shown in Figure 8 presents a Bit Error Rate (BER) vs. Signal-to-Noise Ratio (SNR) performance for different modulation and coding schemes in IEEE 802.16a systems. The x-axis represents SNR, while the y-axis (logarithmic scale) represents BER. The graph compares BASK-1/2, QPSK-1/2, and QPSK-3/4.

- **BASK-1/2 (Blue curve):** This modulation scheme demonstrates the lowest BER at lower SNR values, indicating better noise resilience but lower data transmission efficiency.
- **QPSK-1/2 (Green curve):** Quadrature Phase Shift Keying with a 1/2 coding rate achieves a balance between spectral efficiency and robustness, outperforming BASK-1/2 at higher SNRs.
- **QPSK-3/4 (Red curve):** With a higher coding rate, QPSK-3/4 offers better data rates but exhibits a higher BER at lower SNR values, requiring stronger signal conditions for reliable performance.

From the graph, higher SNR values result in lower BER, signifying improved transmission quality. QPSK-1/2 outperforms QPSK-3/4 at lower SNRs, but QPSK-3/4 becomes more efficient as SNR increases.

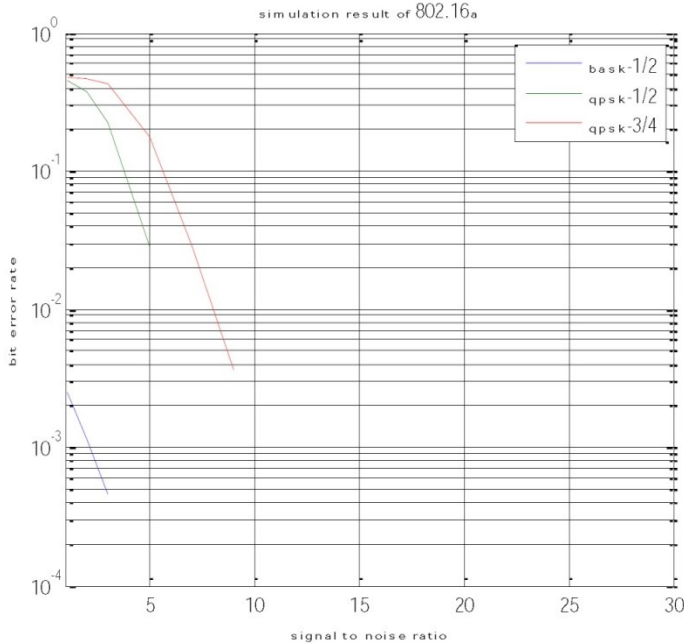


Figure 8
BER performance for concatenated RS-Convolutional codes

Table 2 provides additional numerical insights, confirming that BER decreases as SNR increases. At SNR = 6 dB, QPSK-1/2 has a BER of 0.0280, while QPSK-3/4 has a BER of 0.1778. However, at SNR ≥ 12 dB, both QPSK schemes achieve zero BER.

Table 2
BER at various SNR values for concatenated RS-Convolutional codes

SNR	Bit Error Rate		
	BPSK-1/2	QPSK-1/2	QPSK-3/4
0	0.0025	0.4472	0.4815
2	0.0011	0.3770	0.4642
4	0.0004	0.2255	0.4248
6	0	0.0280	0.1778
8	0	0	0.0293
10	0	0	0.0036
12	0	0	0
14	0	0	0

5. Conclusion

The analysis of BER vs. SNR performance for different modulation and coding schemes in IEEE 802.16a highlights the critical trade-offs between spectral efficiency, reliability, and system robustness. The results indicate that BASK-1/2 performs well at lower SNR levels due to its inherent robustness against noise, but it is limited by lower data transmission efficiency. QPSK-1/2, with its balance between spectral efficiency and error correction capability, demonstrates superior performance compared to QPSK-3/4, particularly at lower SNR values. QPSK-3/4, while offering higher data rates, exhibits a higher BER at low SNRs, making it less suitable for noisy environments. From the BER tables, we observe that at SNR = 6 dB, QPSK-1/2 achieves a BER of 0.0280, while QPSK-3/4 has a BER of 0.1778, confirming that lower coding rates improve reliability in low-SNR conditions. However, at SNR ≥ 12 dB, both QPSK-1/2 and QPSK-3/4 achieve near-zero BER, making higher coding rates more favourable when SNR is sufficiently high. This study emphasizes that modulation and coding scheme selection is crucial in IEEE 802.16a-based systems. The choice depends on the operational environment: lower coding rates for reliability in low-SNR conditions and higher coding rates for better spectral efficiency at high SNR levels.

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