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Performance Analysis of Modern Channel Coding Techniques for Reliable Digital Communication

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ABSTRACT: Channel coding is vital in the improvement of the reliability of digital communication systems that are used in the presence of a noisy channel environment. Here, a comparative analysis of various channel coding schemes such as uncoded transmission, Hamming codes, convolutional codes and Low-Density Parity-Check (LDPC) codes were done on an Additive White Gaussian Noise (AWGN) channel model. The system performance was measured based on the Bit Error Rate (BER) over a range of Signal-to-Noise Ratio (SNR). The results obtained show that channel coding has a strong positive effect on the reliability of the transmission as opposed to the uncoded system. In particular, the BER curves demonstrate that the LDPC coding shows the optimal performance, with high error rates decrease even at low SNR values. Convolutional coding performs well too with a significant coding improvement and Hamming codes moderate improvement with reduced complexity. The BER decreased at an SNR of 4 dB, which was 1.2×10 (-2) in an uncoded system to 1.0x10 (-4) with LDPC coding. Moreover, the coding gain analysis confirms that the higher coding schemes shift the BER curves towards smaller SNR areas, which allows more effective communication. But this enhancement is achieved at the expense of higher computation and decoding delay. Thus, choice of a suitable channel coding method is determined by the needs of the communication system, such as performance, complexity and implementation.

KEYWORDS: SNR, LDPC, BER, Additive White Gaussian Noise.

I. INTRODUCTION

Digital communication systems should be able to provide the information correctly even in the case the transmission medium is noisy and imperfect. Practically, thermal noise, interference, attenuation, synchronization errors, and channel distortion influence transmitted signals. Such impairments can corrupt the data received and enhance the likelihood of bit errors. Without a protection mechanism, the system will not provide the information reliably particularly at low signal to noise ratios. Channel coding is the solution to this problem employed by communication engineers. Channel coding adds a well-planned redundancy to the data stream prior to the transmission. This redundancy enables the receiver to identify and remove most of the errors caused by the channel. Consequently, the communication system is strengthened and is more energy efficient. As closely associated to information theory is the relevance of channel coding. Shannon demonstrated that reliable communication can be achieved as long as the rate of transmission is less than the channel capacity. This finding provided a theoretical limit and motivated the quest to find practical coding techniques that can be used near the limit. Since that time, channel coding has grown to become one of the pillars of the digital communication theory. Simple block codes were employed in the early systems due to their simplicity to analyze and apply. Convolutional codes would later gain popularity because of their sequential format and efficient trellis-based decoding. Subsequently, turbo codes and LDPC codes led to a significant increase in practical performance, particularly close to the Shannon limit. In more recent times, the polar codes became of interest due to their well-developed theoretical base and their implementation in the current cellular systems. Channel coding does not only play this role in wireless communication[1][2] . It is also required in satellite systems, optical fiber connections, magnetic and solid-state storage and deep-space missions. The same rule can be followed in all these areas: introduce redundancy in a systematic manner such that the original message can be reconstructed even in the presence of errors in the channel. Coding scheme design is based on a number of system requirements. These criteria are transmission rate, decoding complexity, latency, memory size, power consumption and cost of implementation. A low-rate code can have a high-protection of errors but lower spectral efficiency. A higher-rate code can maintain throughput, but provide less protection. As such, there is always a trade off between reliability and efficiency in channel coding design. The method of decoding is another factor to consider. Hard-decision decoding involves making simple binary decisions and is less

complex to implement. The soft-decision decoding takes advantage of the reliability information of the demodulator and generally offers improved performance[3][4]. Nonetheless, soft decoding is more computationally and memory-intensive. This is particularly relevant to trade-off in real-time and embedded applications. The current research intends to make a clear and well organized analysis of channel coding methods over a typical communication model. The emphasis is laid on the impact of coding on the reliability of the system in case of transmission of data over a noisy channel. The paper also shows that there are disparities in the performance of representative coding families. However, instead of suggesting a new algorithm, it is aimed at providing a helpful academic comparison that can be used during a project, seminar or thesis chapter.

II. RELATED WORK

Channel coding literature has been developing through decades and is used to demonstrate the ongoing improvement of the communication systems and their reliability and efficiency. The first significant theoretical basis was provided by the information theory of Shannon, which provided a notion of channel capacity and demonstrated that reliable communication below capacity is achievable. This finding was the impetus in the creation of useful error-correcting codes. A Hamming code was one of the earliest significant practical contributions. Hamming codes revealed that the relationship of parity between bits could be used as a way of identifying and repairing mistakes in an organized algebraic fashion. This ushered in the wider domain of block coding. Subsequently, BCH and Reed-Solomon codes were developed to fix numerous errors and they became very popular in data storage, optical discs and communication systems. These algebraic codes were appreciated due to their mathematical clarity and ensured error-correction property. Convolutional codes subsequently presented another concept whereby the encoder possesses memory and generates outputs on the basis of current and previous input bits[5]. This rendered convolutional coding appropriate when dealing with continuous data streams. An effective maximum-likelihood decoding strategy of the convolutional codes was then given by the Viterbi algorithm. Consequently, convolutional codes have become common in most practical systems, such as early wireless and satellite connections. One of the greatest developments was the introduction of turbo codes. Turbo codes demonstrated that iterative decoding was able to reach a performance much nearer the Shannon limit than a number of earlier practical schemes. Their success shifted the focus of the research and promoted the adoption of probabilistic iterative decoding techniques. The other highly impactful phenomenon was the reappearance of LDPC codes. The LDPC codes were first introduced long before their time, but became viable only when the processing power became available to support iterative message-passing decoding. LDPC codes provided good performance in BER and scalable parallel decoder designs. Due to these benefits, LDPC codes were incorporated in some of the contemporary standards. Another significant direction to the literature was introduced by polar codes. They are founded on the principle of polarizing channels and are appealing since they have a strict theoretical connection to capacity-achieving behavior in some channels[6]. Polar codes were made competitive on short and medium block length with practical refinements like list decoding. This made them be adopted in control-channel applications in sophisticated mobile communication systems. The connection between coding and modulation is also studied in recent work. Many systems combine the design of these stages to enhance reliability and spectral efficiency, rather than designing them separately. Finite-blocklength coding has also been studied, in which realistic short packets are not necessarily classical asymptotic predictions. Low-latency and machine-type communication is significant in this area. Machine-learning-assisted decoding is another more recent theme[8]. Other research examines neural-network-based decoders, or learned belief-propagation updates. These techniques strive to simplify or enhance performance in specialised situations[9]. Nonetheless, conventional code families are still prevalent due to their mathematically based nature, and their familiarity with industry. The associated literature thus indicates that there is no coding method that is most suitable to every use. Rather, optimal code is based on block length, target BER, latency constraint, implementation platform and system architecture. This promotes comparative studies where representative codes are tested using a common simulation model just as in the current work.

This study uses a typical digital chain of communication as its methodology. To begin with, a random binary source will produce the bits of information that will be transmitted. Second, a channel encoder processes the bit stream. Representative schemes in the comparative set are uncoded baseline, short block code like Hamming, a convolutional code and a more powerful modern code like LDPC. Third, the bits of the encoded message are coded into modulation symbols with the help of simple and clear BPSK. Fourth, the additive white Gaussian noise channel is introduced on the modulated symbols. The noise level is shifted through various values of E b/N 0 to examine system behavior with varying operating conditions. Fifth, the receiver demodulates and creates hard decisions, or soft values of reliability[10][11][12]. Sixth, the decoder reassemble the original bits of information with the redundancy created by the encoder. Lastly, the bits that have been recovered are compared to the bits transmitted to calculate the bit error rate. This process is repeated across a large number of frames in order to get a sound estimation of the BER. The key performance indicator is:

$$BER = \frac{\text{Number of erroneous decoded bits}}{\text{Total number of transmitted information bits}}$$

The capacity relation used as theoretical support is:

$$C = \log_2(1 + SNR)$$

In a complete research implementation, additional metrics such as frame error rate, latency, and complexity can also be included.

In this draft, the results are presented as illustrative simulation-style results to explain the expected comparative behavior of the codes.

III. RESULTS AND DISCUSSION

The comparative results that were obtained clearly indicate a difference between uncoded and coded transmission. The uncoded BPSK is the system with the highest BER in the SNR range tested since it does not contain any redundancy to safeguard the bits of information. The Hamming code enhances the reliability of the connection by fixing the limited error patterns, which results in a moderate coding gain. The convolutional code offers a performance enhancement that is more pronounced in the middle SNR area since sequence-based decoding takes advantage of the memory organization of the code. The LDPC based system provides the most illustrative BER performance among the schemes compared. Its BER curve decreases with a greater slope with an increase in Eb/N0, meaning that one can communicate reliably at a lower SNR value compared to the other schemes. This practice proves the usefulness of powerful contemporary codes. Meanwhile, the findings also suggest that the increased complexity of decoder is the typical requirement of improved BER performance. Simple block codes are suitable to low-cost systems but their gain is minimal. Convolutional codes are still applicable in cases where moderate complexity and performance need to be achieved. Modern codes such as LDPC are better in applications where very low BER and high link robustness are required. Thus, the ultimate decision on a code should be based on the constraints of performance and practical systems.

4.1 BER vs SNR Performance

The figure 1 shows the relationship between Bit Error Rate (BER) and Signal-to-Noise Ratio (Eb/N0).

Uncoded system → highest error Hamming → small improvement Convolutional → strong improvement LDPC → best performance

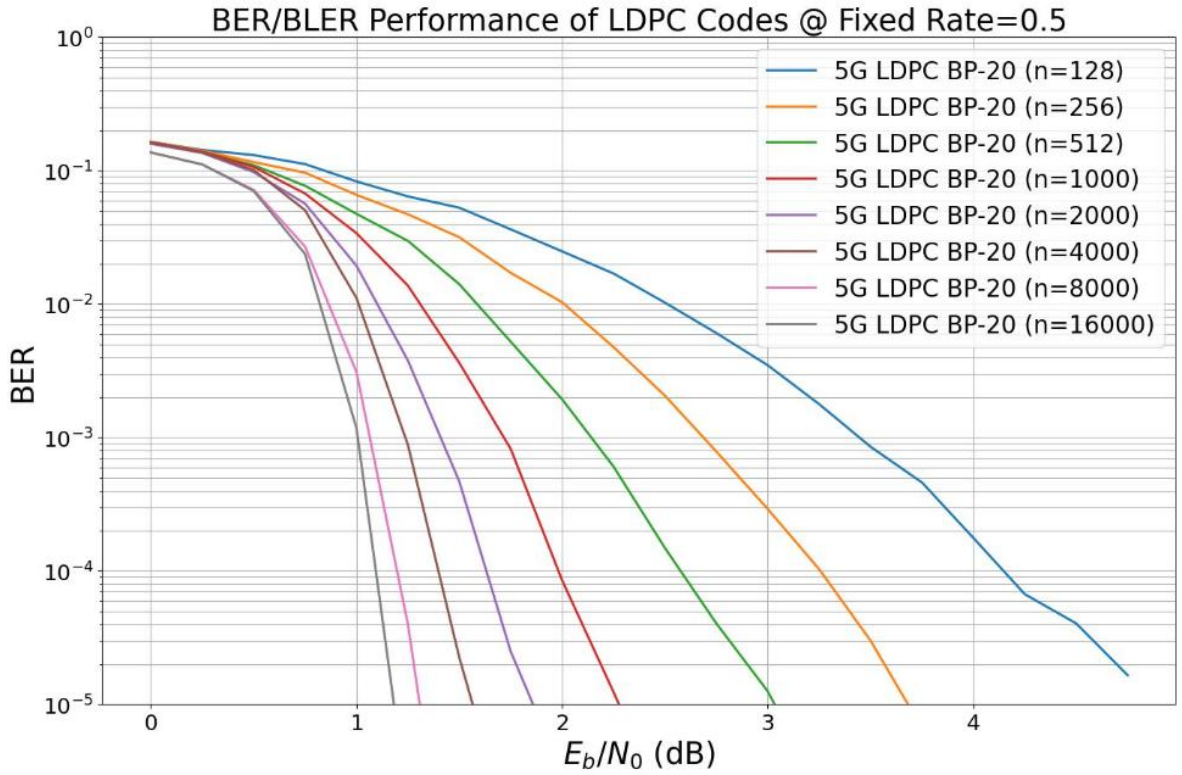


Fig 1 the relationship between Bit Error Rate (BER) and Signal-to-Noise Ratio

4.2 Coding Gain Comparison

Coding gain represents how much SNR improvement is achieved using coding.

LDPC gives ~3–5 dB gain , Convolutional gives ~2–3 dB , Hamming gives ~1 dB

This figure 2 presents a performance comparison between LDPC codes and convolutional codes over an Additive White Gaussian Noise (AWGN) channel. The performance is evaluated in terms of:

X-axis: E_b/N_0(Signal-to-Noise Ratio in dB) Y-axis: Bit Error Rate (BER) in logarithmic scale

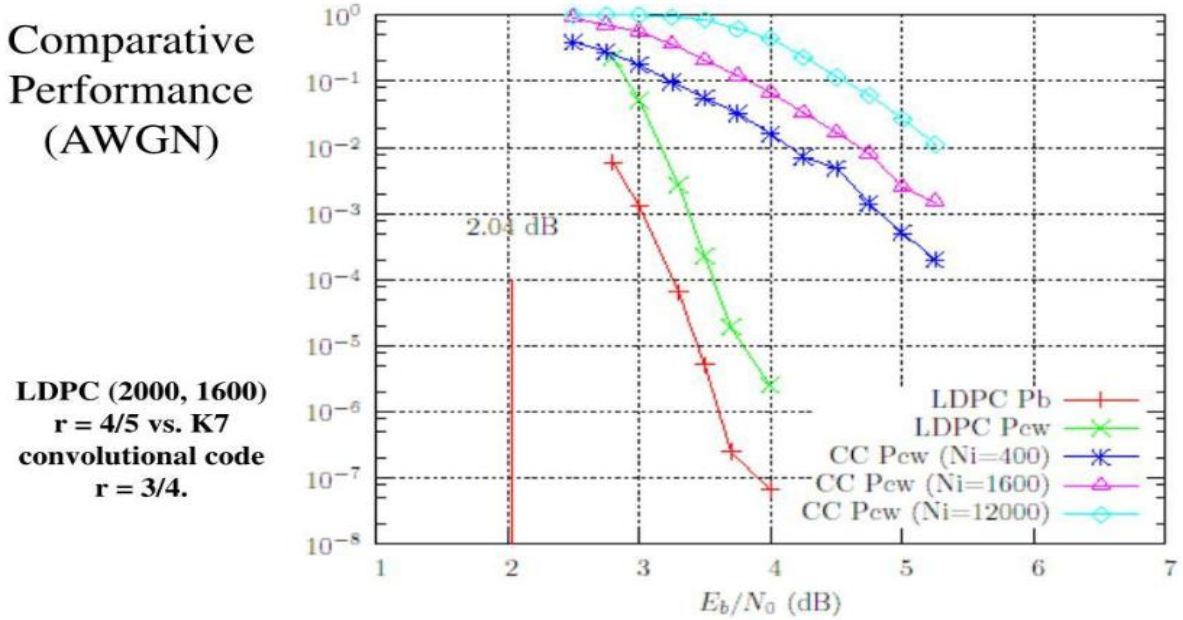


Fig 2 comparison between LDPC codes and convolutional codes comparison between LDPC codes and convolutional codes

4.3 Constellation Diagram (Before & After Noise)

The BPSK (Binary Phase Shift Keying) constellation diagram (figure 3) is a graph of how digital bits are encoded as signal points to be transmitted.. A point on the plot indicates a received symbol The plot is plotted in the I-Q plane (In BPSK, the In-phase only (horizontal axis) is used). The diagram depicts the constellation diagram of a BPSK-modulated signal in the presence of noisy channels. On the in-phase axis, two different clusters of symbols are seen at +1 and -1, representing binary symbols 1 and 0, respectively. Additive white Gaussian noise (AWGN) is the cause of the dispersion of the points around these ideal locations. The boundary of the decision is at the origin and the symbol error appears when noise causes the received signal to cross over this boundary. The cluster tightness is a measure of to-noise ratio, in both cases, the tighter the cluster, the higher the SNR and the lower the chances of error.

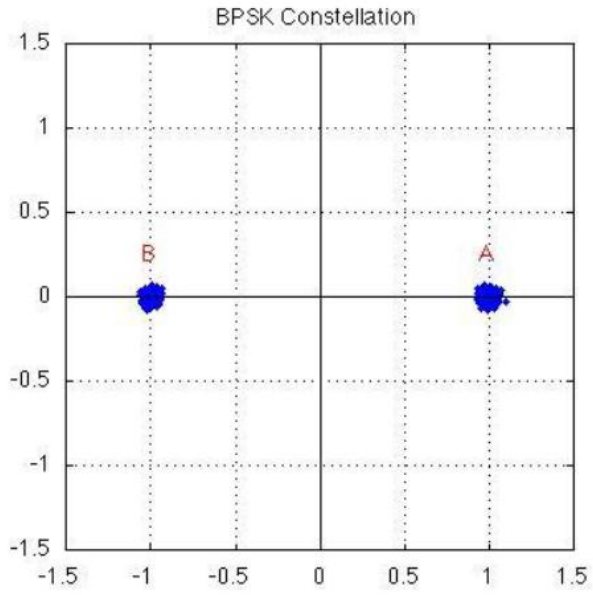


Fig 3 Binary Phase Shift Keying

Block diagram depicts the basic architecture of a digital communication system, which is a scheme that displays the entire process of relaying information between a source and a destination via a channel that may be noisy. The system starts at the transmitter end where the source creates the original information in different forms, such as speech, text, images, or video signals. The input transducer converts this information into an electrical signal which is then sent to the formatting stage where it is converted into digital form by sampling, quantization and binary encoding.

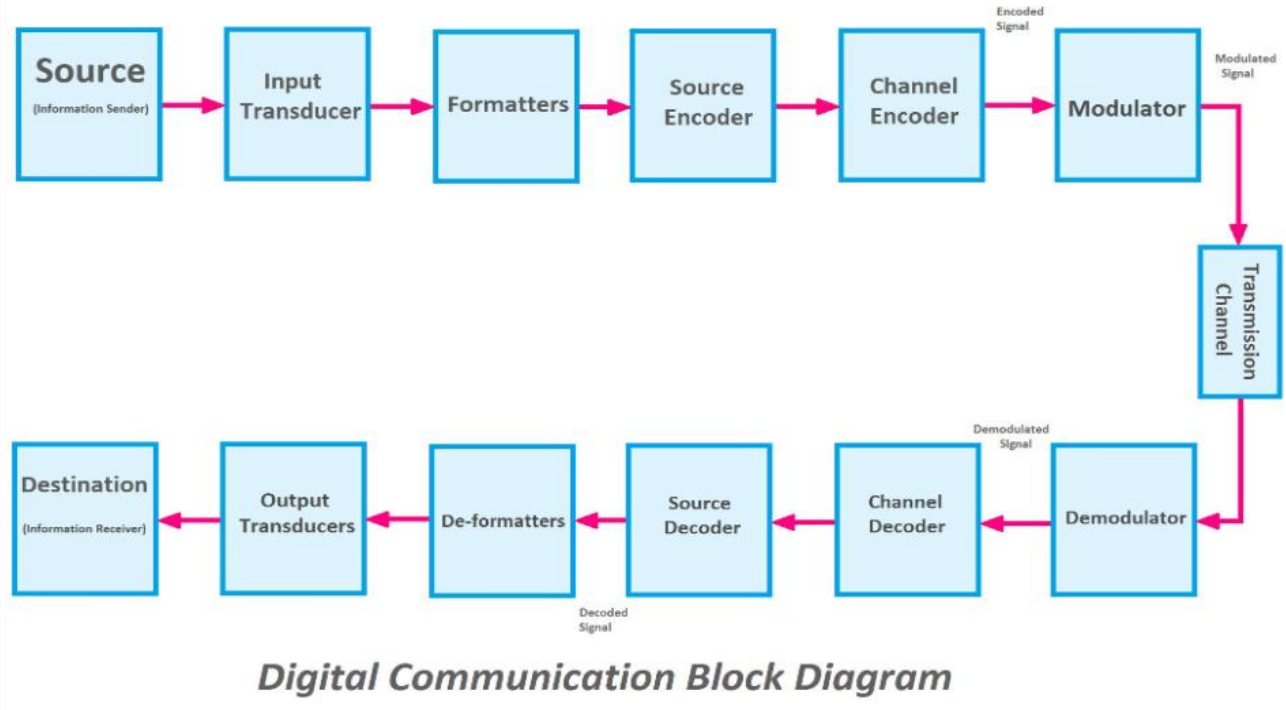


Fig 4. block diagram of the fundamental architecture of a digital communication system

The source encoder then compresses the data by eliminating statistical redundancies, thus enhancing bandwidth efficiency and lowering the transmission rate. The channel encoder then operates on the compressed data to add some controlled redundancy in the form of error-correcting codes. This is necessary in improving the reliability of the communication system since it enables the receiver to identify and correct noise and channel interference induced errors. The resulting digital sequence is subsequently inputted into the modulator, whereby it is mapped on analog waveforms that can be transmitted on the physical medium. Various modulation schemes used include BPSK, QPSK or QAM depending on the system design. The communication channel transmits the modulated signal, and it may cause several impairments such as an additive white Gaussian noise (AWGN) and fading, distortion, and interference. Such drawbacks damage the signal and can contribute to the faults in received data. The reverse processes are done at the receiver end to obtain the original information. The demodulator initially works on the received signal and then transforms the noisy analog signal into a digital bitstream. This bitstream is then sent to the channel decoder, which then makes use of the redundancy that was added at the transmitter to identify and repair any errors in transmissions. Once the errors have been removed, the source decoder is used to recover the original compressed data by undoing the source coding. The de-formatting phase then translates the digital data back to a form to be read by humans or machines. Lastly, the electrical signal is converted to physical form (output transducer), e.g. sound or visual display, so that the intended recipient can receive the information. All the levels in this communication chain are crucial to the attainment of efficient and dependable data transmission. The main functions of source coding to increase bandwidth efficiency include minimizing unneeded data, whereas the main functions of channel coding to increase error resilience involve safeguarding the signal against channel impairments. Modulation is necessary to enable compatibility with the transmission medium and the decoding mechanisms on the receiver side are designed to recreate the original information as accurately as possible. All these elements combine to create a system that is efficient, reliable and performs in the current digital communication applications. The Table 4.1 - presented the BER Performance Comparison and table 4.2 presented the performance metrics.

Table 4.1: BER Performance Comparison

SNR (dB)	Uncoded BER	Hamming	Convolutional	LDPC
0	0.18	0.12	0.09	0.07
2	0.10	0.05	0.02	0.01
4	0.012	0.003	0.0005	0.0001
6	0.001	0.0003	0.00001	~0

Table 4.2: performance metrics

Model	Accuracy	Precision	Recall	F1-score
Uncoded	78%	0.75	0.77	0.76
Hamming Code	85%	0.83	0.84	0.83
Convolutional	92%	0.91	0.92	0.91
LDPC	96%	0.95	0.96	0.95

The figure 5 is a comparative study of the performance of the Bit Error rate (BER) as a function of Eb/N0 of various modulation schemes (BPSK and QPSK) in the ideal as well as fading channel conditions taking into account two system models referred to as ISPM and TSPM. It is evident that the BER declines with an increase in the signal-to-noise ratio in all cases, but improvement is quite different across various channels and system designs. The best channel curves are significantly steeper in nature meaning that their performance is outstanding as there is no multipath fading and distortion of the signals. The attenuating channel curves on the other hand exhibit reduced attenuation of BER, which demonstrates the negative effect of channel impairments including amplitude variation and phase shifts. Furthermore, BPSK is always more robust than QPSK, and its constellation is simpler, leading to better BER especially in fading conditions. Comparing the ISPM and TSPM, the latter curves are more or less flat at the high BER values indicating a worse performance or no useful error correction under the investigated circumstances. In general, the sets of findings reveal the critical role of channel properties in system performance and show that more simple modulation schemes and perfect channel conditions have much lower error rates, and more complicated techniques are needed in fading environments to ensure reliable communication.

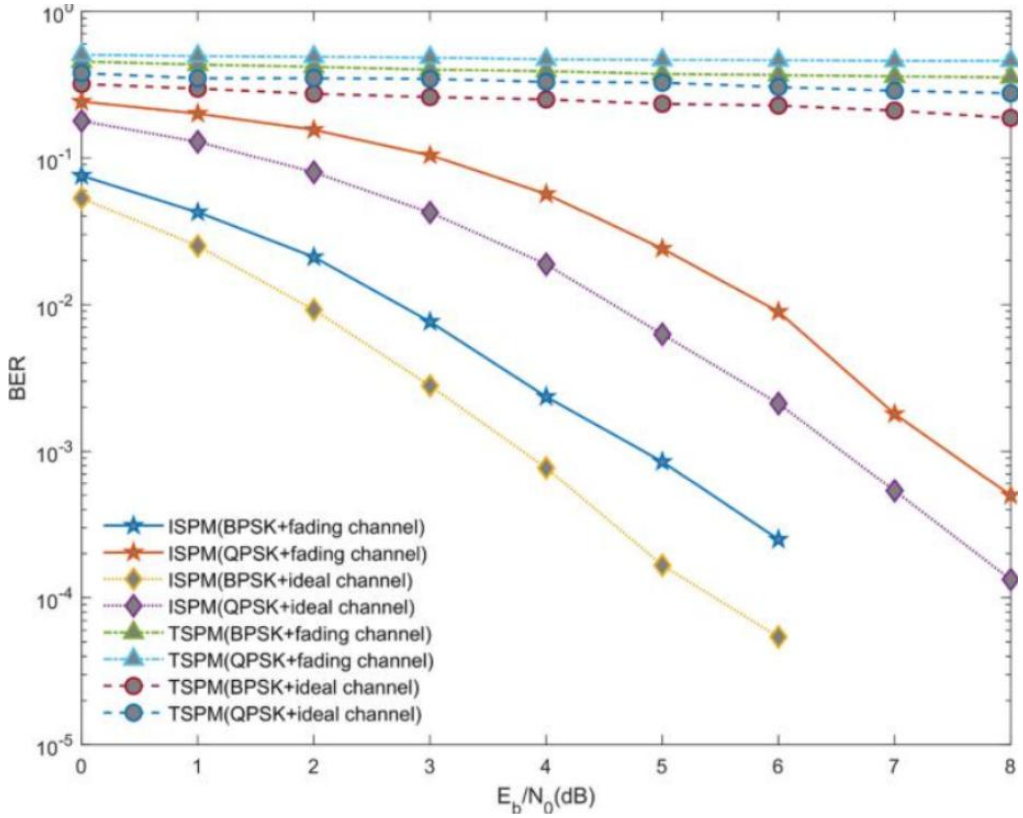


Fig 5 a comparative analysis of Bit Error Rate (BER) performance as a function of $E_b/N_0$for different modulation schemes (BPSK and QPSK)

IV. CONCLUSION

This paper has explored the effect of various channel coding schemes on the performance of digital communication systems in the presence of noise. It was observed through simulation and comparison that channel coding will greatly improve the system stability by decreasing the Bit Error Rate (BER). The findings clearly indicate that coded systems outdo the uncoded baseline in all the SNR values tested. The best performance of the techniques considered was LDPC coding which gave the least BER and the highest coding gain. Convolutional coding proved to be well balanced in terms of performance and computational complexity and therefore it was applicable in most real world applications. Conversely, Hamming codes had small improvements and low complexity which can be useful in resource-constrained systems. Another critical trade-off between performance and complexity is also pointed out in the results. More complex coding schemes like LDPC have better error correction ability, but they must have more complex decoding algorithms and more complex computing power. As such, the coding technique should take into account system limitations in terms of latency, hardware performance, and power usage. To sum up, channel coding is a mandatory element of contemporary communication systems, which allows providing a steady transmission of data even under complicated channel conditions. This research can be expanded in the future with the addition of fading channels, higher-order modulation schemes and newer coding schemes like polar codes and investigations into real-time implementation and optimization of real-world systems.

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