Analysis and application research on key issues of channel coding

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Abstract. Channel coding plays a crucial role in enhancing the reliability and efficiency of communication systems, particularly when transmission channels are disrupted by noise and interference. This paper presents an in-depth review of various channel coding techniques, their applications, and future research directions. Key topics discussed include prevalent channel coding methods, such as repetition codes, convolutional codes, LDPC codes, turbo codes, and polar codes. The paper also delves into the selection of suitable channel coding parameters and their applications in digital TV, mobile and satellite communications, unmanned aerial vehicle data links, speech communication, and underwater acoustic channels. Moreover, the paper explores the performance analysis and comparison of different channel coding techniques, shedding light on their strengths and weaknesses. Lastly, the paper identifies emerging trends and challenges in channel coding research, providing valuable insights for researchers and practitioners in the field of communication systems. By examining these techniques and future directions, this comprehensive overview aims to contribute to the development of more robust and efficient channel coding schemes for a wide range of communication applications.

Keywords: channel coding, error correction, modulation, convolutional codes, LDPC codes, polar codes, wireless communication, IoT, 6G, machine learning.

1. Introduction

Channel coding is a vital technique for boosting the reliability and efficiency of communication systems, especially when noise and interference disrupt transmission channels [1]. Since Shannon's groundbreaking work on information and coding theory in 1948, research on achieving reliable transmission over unreliable channels has persisted, with channel coding playing a central role [2].

The emergence and popularization of 5G communication further underscore the importance of channel coding [3]. This article investigates the specific applications of channel coding and the efficacy of various coding methods to prepare for future challenges and opportunities in the field [4].

Shannon's second coding theorem, articulated in his seminal paper "A Mathematical Theory of Communication," established that there exists a coding method capable of enabling transmission at a rate R nearly as high as the channel capacity C, while still maintaining an extremely low transmission error rate [5]. This theorem has inspired researchers to explore different encoding schemes that approach this theoretical limit, known as the Shannon capacity [6]. Essentially, Shannon's theory suggests that a coding scheme exists that can achieve exceedingly low error probabilities for transmission rates less

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than or equal to the channel capacity, and researchers continue to work towards developing such schemes. The quest for these optimal encoding schemes is an active area of research in information theory, as they hold the potential to revolutionize communication by enabling faster and more reliable data transmission [7].

Significant advancements have been made in linear Gaussian channel models, such as Turbo codes and LDPC codes [8]. However, developing encoding schemes that approach theoretical limits for wireless communication remains challenging due to the nonlinear, time-varying properties of wireless channels. Current global research efforts focus on enhancing coding techniques, such as LDPC, turbo, polar, and product codes, to address communication system challenges. Moreover, researchers investigate integrating multiple coding schemes to improve performance in the face of channel impairments [9]. In China, the development of customized channel coding techniques for domestic communication systems, including satellite and wireless communication, is an active area of exploration [10].

2. Introduction to basic knowledge

2.1. Fundamentals of channel coding

In communication systems, channel coding is a strategy implemented to bolster the reliability of data transmission when faced with noisy channels. It involves adding redundant information to detect and correct errors. Coding schemes vary in complexity and performance, with some adding simple redundancy, while others use more complex algorithms for higher error correction capabilities. The primary goal is to enable reliable communication with minimal errors, and researchers continue to explore new coding schemes to approach the theoretical limit of communication capacity. This improves the efficiency and reliability of communication systems, making them more suitable for modern applications.

2.2. Common channel coding techniques

2.2.1. Repetition code. Repetition code is a simple error-correcting code that works by transmitting each bit of a message multiple times. The sender duplicates each bit of the message, and the receiver performs a majority vote to determine the correct bit. The idea behind the repetition code is that the redundant bits can be used to detect and correct errors that may occur during transmission.

2.2.2. Convolutional codes. Convolutional codes operate by encoding an ongoing stream of input data through the utilization of a shift register and a collection of code coefficients. The shift register maintains a limited quantity of preceding input bits, shifting them in a temporal order as new input bits are introduced. The code coefficients serve to generate the output bits, which are subsequently transmitted over the communication channel. Upon reception, the decoder employs specific algorithms to ascertain the most probable sequence of input bits responsible for creating the received code sequence. By comparing the received code sequence to all potential input sequences, the decoder selects the sequence with the highest likelihood [1].

2.2.3. LDPC codes. LDPC (Low-Density Parity-Check) codes represent a category of linear error-correcting codes employed in digital communication and data storage systems. Their operation is grounded in the principle of parity-check matrices. The generator matrix of an LDPC code is characterized by its sparse nature, containing a minimal density of ones. When transmitting a message utilizing LDPC codes, the message undergoes encoding through multiplication with the generator matrix. Subsequently, the resulting codeword is conveyed over the communication channel. At the receiving end, the obtained codeword undergoes error checking by being multiplied with the parity-check matrix. This parity-check matrix assists in pinpointing the error locations within the received codeword [6].

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LDPC codes are known for their excellent error-correction performance, low complexity, and design flexibility. They are widely used in various communication standards, including Wi-Fi, WiMAX, and DVB-S2. LDPC codes can achieve near-capacity error-correction performance with relatively low complexity, making them suitable for high-speed data transmission applications.

2.2.4. Turbo codes. Turbo codes, a class of error-correcting codes in wireless communication systems, are renowned for their exceptional data transmission and error correction capabilities. The operational principle encompasses three primary stages: encoding, interleaving, and decoding. Encoding employs parallel concatenation of convolutional encoders, while an interleaver reorganizes input data to minimize error correlation among parity bits. Decoding is an iterative procedure utilizing soft-input soft-output decoders, which exchange extrinsic information to ultimately reconstruct the original data sequence with elevated reliability. By employing parallel concatenated codes, interleaving codewords, and iterative decoding, turbo coding bolsters the reliability of digital communication systems, refining the decoding process and facilitating increased data rates.

2.2.5. Polar codes. Polar coding, a pioneering error-correcting code in digital communication systems, was devised by Erdal Arikan and employs binary tree structures and channel polarization to convert original data bits into highly reliable bits. The working principle is based on channel polarization, separating the original data bits into two sets: highly reliable bits and less reliable bits. A binary tree is constructed with the original data bits at the leaves, and the tree's structure is created using a recursive kernel matrix called the Arikan matrix. This matrix is applied iteratively to the input bits, generating intermediate nodes in the tree and eventually reaching the root node, which contains the combined reliability information of all original data bits. Through successive applications of the Arikan matrix, the channels become increasingly polarized, enabling efficient error correction by focusing on correcting the less reliable bits. Due to its low complexity and flexibility, polar coding has been adopted for 5G wireless communication, improving system reliability, efficiency, and data transfer rates, making it a significant advancement in the fields of information theory and communication systems [7].

2.3. Channel coding parameter selection method
Selecting appropriate channel coding parameters is vital for optimizing error-correcting codes in digital communication systems. Various methods can be employed, such as simulation-based, analytical, and machine learning techniques. Simulation-based approaches assess coding schemes' performance over channels, while analytical models use statistical channel models to predict performance. Machine learning algorithms examine extensive data sets to discern correlations between channel characteristics and coding scheme effectiveness. Typically, a combination of these methods is implemented to choose coding parameters that fulfill system requirements, enabling reliable communication even in environments with noise and interference.

3. Channel coding application case study

3.1. Channel coding in digital tv signal transmission
In digital TV signal transmission, channel coding techniques such as forward error correction (FEC) [5], convolutional coding, and turbo coding are essential for maintaining signal reliability amidst noise and interference. FEC adds redundancy to the data stream for error detection and correction, while convolutional and turbo coding use advanced algorithms to encode data, bolstering its resilience against noise and interference. Preserving signal quality in digital TV transmission is critical due to potential factors like atmospheric conditions and electrical interference that may compromise signal integrity.

3.2. Channel coding in mobile communications
Channel coding in mobile communications is essential for reliable data transmission across noisy wireless channels, utilizing techniques like convolutional, turbo, LDPC, and polar coding to introduce

redundancy for error detection and correction. The selection of a coding method depends on factors such as data rate, latency, and error-correction requirements. When designing a coding scheme, it is crucial to choose the appropriate code rate, word size, and decoding algorithm. Modern mobile systems, including 4G and 5G, frequently employ adaptive channel coding schemes, adjusting parameters according to channel conditions to maintain high-quality connections and optimize resource use.

3.3. Channel coding in satellite communications

DVB-S2 satellite systems employ a forward error correction system using cascaded BCH and LDPC codes, characterized by a sparse parity-check matrix for efficient decoding algorithms with near-Shannon-limit performance. This approach reduces demodulation thresholds and allows longer codes with manageable decoding complexity. Advanced Satellite Broadcasting System (ABS-S) utilizes LDPC codes with stronger error correction capabilities and shorter frame lengths, eliminating the need for BCH codes. Turbo codes, adopted in satellite communications due to their excellent error-correcting performance, employ parallel concatenation of convolutional codes with an interleaver for iterative decoding. Polar codes, a newer capacity-achieving class of channel codes with low encoding and decoding complexity, are being considered for future satellite communication systems. As encoding methods evolve, digital satellite radio and television systems continue to improve [3].

3.4. The data link of unmanned aerial vehicle

China is rapidly advancing its UAV data link systems, focusing on channel encoding technology to enhance high-speed communication. Comparing LDPC codes, convolutional codes, and Turbo codes in Rayleigh and Rician fading channels, simulations show LDPC codes outperform others in both short and long code scenarios. By implementing LDPC codes, UAV data link systems can achieve higher data rates, improved error-correction capabilities, and better overall performance. This is essential for real-time monitoring and control in applications such as surveillance, disaster management, and agriculture. As the UAV industry grows, optimizing advanced channel encoding techniques remains crucial for UAV data link systems' success.

5G technology encompasses three main use cases: enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC), and massive machine-type communication (mMTC). In the eMBB context, a code excelling in performance for long block lengths and fast decoding is desired. To meet this requirement, the 3GPP has already adopted LDPC codes for data channels and Polar codes for control channels. For the URLLC scenario, a code with small packet sizes, low code rates, no error floor, resilience over fading channels, manageable decoding complexity, and a user-friendly rate matching mechanism is required. Turbo codes are not suitable for this scenario due to their increased decoding complexity and subpar performance at low code rates with shorter block lengths. LDPC codes also underperform for short block lengths and low code rates. In contrast, Polar codes provide exceptional performance with a range of code rates and code lengths through straightforward puncturing and code shortening mechanisms. They can achieve 99.999% reliability, feature low-complexity decoding algorithms, and consume minimal power, making them well-suited for both URLLC and mMTC scenarios [8]. As a result, Polar codes emerge as a strong candidate for 5G NR scenarios, particularly in the context of URLLC and mMTC use cases. Their unparalleled performance, adaptability in code rates and code lengths, reduced decoding complexity, and low power consumption render them an ideal solution for the demanding requirements of 5G networks

3.5. Speech communication

In speech communication, polar code is a suitable channel coding scheme for speech communication due to their capacity-achieving property, low complexity, and ability to efficiently use the channel. The structured nature of speech signals allows Polar codes to select only noiseless channels, reducing the probability of error and improving efficiency. Additionally, Polar codes can be constructed with various code rates and lengths to meet the specific requirements of the speech communication system.

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Numerical simulations demonstrate that Polar codes outperform LDPC codes over both AWGN and Rayleigh channels, making them a promising choice for speech communication applications.

3.6. Underwater acoustic (UWA) channels

Underwater acoustic (UWA) channels present significant challenges for wireless communication due to their rapidly changing nature, extended multipath delays, and substantial frequency-dependent attenuation. Ensuring effective error-correction coding is essential for UWA communication systems, particularly when dealing with short or medium-length bit inputs. Various coding techniques have been investigated, including Convolutional Codes, RS block codes, Turbo codes, and Non-binary LDPC coding [4].

Protograph LDPC codes are recommended for implementation in UWA communication systems due to their linear encoding and decoding complexity, coupled with their uncomplicated structure. These attributes lead to a reduction in overall channel coding time, facilitating real-time and reliable UWA communication. As a subset of LDPC codes, Protograph-based LDPC codes possess swift encoder structures and have found applications in ultra-wideband (UWB) communication, space communication, and partial response (PR) channels in magnetic recording systems. These codes demonstrate exceptional error-correction capabilities in channels with inter-symbol interference (lSI) and have been proven to outperform MacKay's LDPC codes in UWA channels. The introduction of Protograph LDPC codes aimed to enhance encoding and decoding speed while maintaining high error-correction performance in UWA communication.

4. Performance analysis and comparison of channel coding

4.1. Performance comparison of different channel coding techniques

Performance comparison of different channel coding techniques is crucial for selecting the most suitable method for enhancing reliability and efficiency in communication systems. Convolutional, turbo, LDPC, and Reed-Solomon coding each have their own advantages and drawbacks. Assessing their performance involves evaluating error-correction capabilities, coding efficiency, complexity, and decoding delay. Coding gain measures error-correction, with higher values indicating improved SNR and better performance. Coding efficiency depends on the rate, with higher rates signifying efficient data transmission but reduced error-correction capabilities. Complexity reflects the computational resources required, with lower complexity being preferable. Decoding delay evaluates the time needed to decode received data, with shorter delays being more desirable [3]. Convolutional coding offers simplicity and low complexity but lower coding gain. Turbo and LDPC coding provide higher coding gain and efficiency but with increased complexity, making them suitable for high-data-rate applications. Reed-Solomon coding, a non-binary cyclic code, excels in error detection and correction for data storage and broadcast applications. The selection of an appropriate coding technique depends on specific system requirements and desired trade-offs between performance factors.

4.2. Comparison of channel coding and modulation methods

Channel coding and modulation are two important techniques used to enhance wireless communication. Channel coding adds redundancy to the transmitted data for error correction, while modulation adjusts the signal to optimize transmission.

A key factor in comparing channel coding and modulation is their impact on system performance, including error rate, spectral efficiency, complexity, and power consumption. Convolutional coding is a simple technique that provides moderate error correction, while turbo and LDPC coding offer higher error correction at the cost of increased complexity. Modulation schemes vary in spectral efficiency and error correction capabilities, with higher-order schemes providing greater spectral efficiency but requiring more signal-to-noise ratio (SNR) and being more susceptible to errors. By comparing and selecting the appropriate combination of channel coding and modulation techniques, wireless communication systems can achieve optimal performance and efficiency.

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4.3. BER Analysis in channel coding applications

BER analysis is used to evaluate the performance of different channel coding schemes by measuring the rate of bit errors in received data and comparing it to the theoretical error rate predicted by the coding scheme [6]. The BER depends on factors such as the SNR of the received signal, the coding rate, and the complexity of the decoding algorithm. Higher SNR results in lower BER, higher coding rate results in higher spectral efficiency but also higher BER, and more complex decoding algorithms provide better error-correction capabilities but require more computational resources. BER analysis can help in selecting the appropriate coding scheme for a given application and optimizing parameters to achieve a specific BER at a lower SNR, improving overall performance of the communication system.

5. Future development of channel coding

5.1. Application prospects of channel coding

In IoT applications, channel coding plays a critical role in enabling reliable data transmission over noisy wireless channels. For instance, in smart city applications, channel coding is used to transmit sensor data and enable remote control of devices such as traffic signals and streetlights.

In agriculture, it can optimize irrigation, fertilizer application, and pest control, leading to increased crop yields and reduced waste. In connected vehicles, it improves vehicle safety, traffic flow, and enables autonomous driving. About smart energy, channel coding facilitates real-time monitoring and efficient distribution of energy resources. In home automation, it enables remote control and monitoring of smart home devices for convenience, security, and energy efficiency. In addition, it helps track pollution levels, predict natural disasters, and implement mitigation strategies in environmental monitoring. For, retail and supply chain, it also contributes to enhanced operational efficiency and customer experience through inventory tracking and automated checkout systems. Furthermore, channel coding is also used in wearable devices and medical implants, where reliability and low power consumption are crucial factors. In 6G communication, channel coding will be essential for high-speed, low-latency communication required by emerging applications such as virtual and augmented reality, autonomous vehicles, and tactile internet. To meet stringent performance requirements, advancements in channel coding will include new modulation and coding techniques, enhanced channel estimation methods, and integration with technologies like Massive MIMO and beamforming. Machine learning and artificial intelligence will play a significant role in optimizing channel coding schemes, adapting to changing conditions and minimizing complexity. Additionally, 6G channel coding will need to support distributed processing in edge computing, ensure data security and privacy, and adapt to heterogeneous networks comprising satellite, terrestrial, and aerial systems [8]. These advancements will facilitate seamless connectivity and optimal performance in the 6G era.

5.2. Future development direction of channel coding technology

Two significant trends in channel coding research are the development of low-latency coding schemes and coding schemes optimized for specific communication channels. Low-latency coding schemes are critical for real-time applications, and researchers are exploring new techniques such as polar codes, LDPC codes, and turbo codes. Coding schemes optimized for specific communication channels, such as wireless and satellite channels, have also been developed to achieve maximum performance. The trend is towards more integrated and efficient communication systems where source and channel coding are optimized together. Future developments may focus on finding more effective ways to combine source and channel coding and incorporating optimization techniques such as machine learning and artificial intelligence.

Adaptive channel coding, including rate-compatible LDPC codes, is gaining significance in addressing fluctuating channel conditions in wireless communication systems. Researchers are also exploring the potential of turbo codes and polar codes to enhance system reliability and efficiency. With the ongoing evolution of wireless communication technology, it is anticipated that more sophisticated adaptive coding schemes will emerge to satisfy the requirements of future systems.Channel coding plays a crucial role in modern communication systems by enabling reliable transmission of digital information over noisy channels. However, challenges such as efficient error-correcting code design, balancing coding rate and decoding complexity, and optimizing coding schemes for emerging applications such as wireless and quantum communication systems still need to be addressed. Furthermore, the trend towards machine learning-based communication systems presents new opportunities and challenges for channel coding research. To meet these challenges, researchers need to collaborate across multiple disciplines and develop innovative coding schemes that can meet the growing demands of modern communication systems. The future development of channel coding technology in wireless networks may involve further optimization of existing coding schemes, development of new coding schemes, integration of coding and modulation techniques, and exploration of new coding techniques such as machine learning-based coding and quantum coding [7].Future research in channel coding will concentrate on addressing the challenges posed by emerging wireless applications, focusing on optimizing existing coding schemes and developing new ones with improved error correction performance. Integrating coding and modulation techniques, along with exploring novel approaches such as machine learning-based coding and quantum coding, will play a pivotal role in meeting the demands of future wireless networks. Collaboration across multiple disciplines will be essential to drive innovation and create cutting-edge coding schemes that can keep up with the rapidly evolving landscape of wireless communication.

6. Conclusion

Channel coding is a critical aspect of contemporary communication systems, enabling digital information to be reliably transmitted over noisy channels. The field of channel coding has witnessed significant advancements in recent decades, with numerous error-correcting codes proposed and extensively employed in practice. However, challenges remain, including designing efficient codes that counteract channel noise and interference while maintaining low decoding complexity. Furthermore, the implementation of channel coding in emerging applications, such as wireless and satellite communications, presents novel challenges and opportunities. The trend towards machine learning-based communication systems also introduces new possibilities for channel coding research. In summary, ongoing research and development in channel coding are essential to satisfy the requirements of modern communication systems and emerging technologies.

References

[1] Arora K, Singh J, Randhawa Y S. A survey on channel coding techniques for 5G wireless networks[J]. Telecommunication Systems, 2020, 73: 637-663.
[2] Indoonundon M, Pawan Fowdur T. Overview of the challenges and solutions for 5G channel coding schemes[J]. Journal of Information and Telecommunication, 2021, 5(4): 460-483.
[3] Kurka D B, Gündüz D. DeepJSCC-f: Deep joint source-channel coding of images with feedback[J]. IEEE Journal on Selected Areas in Information Theory, 2020, 1(1): 178-193.
[4] Dai J, Wang S, Tan K, et al. Nonlinear transform source-channel coding for semantic communications[J]. IEEE Journal on Selected Areas in Communications, 2022, 40(8): 2300-2316.
[5] Choi K, Tatwawadi K, Grover A, et al. Neural joint source-channel coding[C]//International Conference on Machine Learning. PMLR, 2019: 1182-1192.
[6] Bourtsoulatze E, Kurka D B, Gündüz D. Deep joint source-channel coding for wireless image transmission[J]. IEEE Transactions on Cognitive Communications and Networking, 2019, 5(3): 567-579.
[7] Farsad N, Rao M, Goldsmith A. Deep learning for joint source-channel coding of text[C]//2018 IEEE international conference on acoustics, speech and signal processing (ICASSP). IEEE, 2018: 2326-2330.
[8] Choi K, Tatwawadi K, Grover A, et al. Neural joint source-channel coding[C]//International Conference on Machine Learning. PMLR, 2019: 1182-1192.

DOI: 10.54254/2755-2721/15/20230809

[9] Zarcone R, Paiton D, Anderson A, et al. Joint source-channel coding with neural networks for analog data compression and storage[C]//2018 Data Compression Conference. IEEE, 2018: 147-156.
[10] Balsa J, Domínguez-Bolaño T, Fresnedo Ó, et al. Transmission of still images using low-complexity analog joint source-channel coding[J]. Sensors, 2019, 19(13): 2932.