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SURVEY

# A Reviewing Approach to Analyze the Advancements of Error Detection and Correction Codes in Channel Coding With Emphasis on LPWAN and IoT Systems

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**ABSTRACT** Error control coding improves reliability and efficiency of wireless communication systems. This research delves into the latest advancements in error control coding schemes for wireless communication systems, with a specific focus on their application within the domain of Low Power Wide Area Networks (LPWANs) such as Narrowband Internet of Things (NB-IoT) systems, LoRa energy-efficient hardware design, random access control systems, and wireless sensor networks. In the context of LPWANs, particularly NB-IoT systems, we investigate the adaptive coding and modulation (ACM) in NB-IoT systems, which adapts coding rates and modulation techniques to changing channel circumstances. Comprehensive analysis of the literature review shows that the proposed approaches are more energy efficient and less error-prone than fixed coding and modulation schemes. Using Cell Design Methodology (CDM), Single Error Correction (SEC) codes are optimized for energy efficiency. Power and energy efficiency have improved in standard CMOS and CDM logic systems. This impacts IoT devices, memory storage, and security systems. Next, Forward Error Correction (FEC) is examined for ALOHA-based random-access control systems wherein packet loss rate and spectral efficiency metrics are mathematically calculated. FEC is beneficial, especially when time and frequency synchronization diverge. Monte Carlo simulations studied in the literature shows that FEC improves satellite communication systems. This review establishes benefits of FEC, notably in satellite communications systems. In addition, Wireless Sensor Networks (WSNs) error control techniques and network reliability and performance are examined along with Convolutional, Turbo, Low density parity check codes(LDPC), and Polar error correction coding (ECC) methods. We learn about their benefits, drawbacks, and implementation challenges by assessing their efficacy, efficiency, and applicability in wireless sensor networks (WSN) applications. This study further highlights advancements of energy-efficient error control coding when, integrated into network designs alongwith the trade-offs between efficacy and intricacy to help improve wireless communication networks. Finally, this study summarizes current error control coding approaches for wireless communication systems. We provide insights into improving reliability, energy conservation, and efficacy by examining ACM, CDM, FEC, and error correction coding (ECC) across varied domains including LPWAN and IoT technologies with earnest hope to facilitate researchers, engineers, and professionals working in the field of error control coding in wireless communication.

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**INDEX TERMS** Low complexity channel coding, low complexity error coding, wireless sensor networks, efficient error coding and low power error coding.

## I. INTRODUCTION

The Internet of Things (IoT) has revolutionized our lives by enabling devices to connect to the internet. However, this technology has also presented a number of communication challenges such as efficient data transfers, optimal bandwidth utilization, and improved data reliability. To overcome these obstacles, it is essential to establish strong connections between devices and networks to enable seamless exchange of data. This will aid in making faster and more intelligent decisions that can positively impact various physical phenomena, resulting in a better overall ecosystem. Several studies have predicted that IoT will play a significant role in our lives in the years to come, including in areas such as smart healthcare, transportation systems, cities, industries, waste management, and machine-to-machine (M2M) communications. As such, it is important to prioritize the development and implementation of IoT technology to realize its full potential and enhance our daily lives [1], [2], [3], [4], [5]. Numerous wireless technologies have emerged to support IoT services. Short-range WSNs and long-range cellular networks are amongst them. Examples of short-range technologies for IoT include Bluetooth, Near Field Communication (NFC), Z-wave, Wireless Local Area Networks and IPv6 Low Power Wireless Local Area Networks. However, these short-range technologies face several challenges such as weak network robustness, high deployment cost, and limited network scalability. In contrast, cellular network based IoT faces issues related to network deployment cost, complex network infrastructure, and short network lifetime [6].

The coverage of short-range wireless technologies such as Bluetooth and ZigBee is limited, while cellular technologies are not power-efficient for prolonged usage. The Low Power Wide Area Network (LPWAN) has surfaced as a practical solution for IoT applications which necessitates extensive transmission ranges, minimal power consumption, and economical implementation. LPWAN technologies have the capability to transmit concise messages over extensive distances, up to 40 km in rural areas and 10 km in urban regions, rendering them highly suitable for Internet of Things (IoT) applications which require infrequent message transmissions over long distances [7]. LPWAN technology has been developed as a viable solution to address the challenges associated with long-range transmission, low power consumption, and cost-effective deployment for IoT applications. LPWAN has gained popularity in IoT devices due to its ability to cover a vast area with minimal power consumption, efficient utilization of bandwidth, and cost-effective network implementation. LPWAN-based machine-to-machine (M2M) communication enables IoT devices to monitor their environment and interact with it from any location and at any time. LPWAN technology is known for its extended battery life of at least 10 years and its ability to provide extensive coverage over long distances. In rural areas with a clear Line of Sight (LoS) coverage can reach up to 40 km while in urban areas with poor LoS coverage can extend up to 10 km. LPWAN is widely recognized as a prominent wireless technology for wide area networks to effectively meet the objectives of the IoT, thus making it a highly suitable option for IoT applications [8]. The extended transmission range of LPWAN is facilitated by its capacity to transmit data over considerable distances originating from individual devices. In order to attain this objective, unlicensed LPWAN technologies, namely LoRa, SigFox, and DASH7, employ Industrial, Scientific, and Medical (ISM) sub-Gigahertz (GHz) band frequencies such as 868 MHz and 915 MHz as reported in reference [9].

Haystack Technologies has developed DASH7 XR Mode version 2.0, which can significantly improve the range performance of LoRa networks. The DASH7 XR Mode uses NASA-derived error correction resulting in an enhancement in range performance by 10-20 times when compared to a comparable LoRaWAN implementation. With this advancement, developers can safely work with better data rates, expect extended battery life, and lower levels of packet error. The recent combination of three encoding technologies which allows LPWAN-types of packets to yield maximum gain has been used to enhance the DASH7 networking stack. The improvements in the Haystack decoder implementation allow data rates as high as 50 kbps an adaptive modulation of encoding rate, and better real-world signal propagation over LoRaWAN by 14 dB at maximum range. With the use of the DASH7 XR Mode, there is no longer a distinction between DASH7 LAN mode and DASH7 XR Mode. Furthermore, the range is improved across all features, and multi-year battery life is preserved along with the implementation of on-demand Global Navigation Satellite System (GNSS)/ Global Positioning System(GPS) [10].

### A. ROTATING POLARIZATION WAVE

The emerging LPWAN technology known as rotating polarization wave offers a reliable solution for M2M in IoT applications. It is a very recent development and no commercial module available in the market however, rotating polarization wave (RPW) aims to provide good communication in unstable environments. In industrial environments, reflected waves can interfere with transmissions between transmitters and receivers in the absence of a direct line of sight. RPW overcomes this challenge by using rotating polarization to improve the signal strength and error performance of the received signal. Compared to uni-polarized signals, RPW can increase the received signal strength by up to 10dB, and experiments in industrial environments have demonstrated the effectiveness of RPW technology. Although the RPW technology is still in infancy but holds promise for IoT applications in challenging environments [11], [12], [13].

The research in [14] compares the error performance of LoRa and RPW for LPWANs in different propagation environments. LoRa offers higher sensitivity and link budget but RPW outperforms LoRa in terms of bit error rate (BER) performance and range, especially in fading conditions. For critical IoT applications which require high data rates and coverage, RPW is a more reliable and robust LPWAN technology. The paper provides valuable insights into the comparison of these LPWAN technologies and their suitability for different applications. The paper also discusses future work to analyze coverage in remote areas, spectral and energy efficiency, and depolarization effects.

### *B. SONY ELTRES*

Sony Eltres is a low-power wireless technology and uses electromagnetic waves to send data between devices. It operates at a frequency of 2.4 GHz and has a range of up to 30 meters. Sony Eltres is designed to be energy-efficient and can run on a single battery for up to 10 years. It also has the ability to transmit data in both directions, allowing for two-way communication. One of the unique features of Sony Eltres is its ability to detect the presence of people or objects, making it suitable for use in various applications including home automation, security systems, and asset tracking. ELTRES is a recently introduced IoT-based device that connects IoT devices across the world. It is a low-power wide-area network device capable of providing previously unseen visualization. ELTRES can establish stable communication over 100km at a speed of 100km/h while consuming very little battery power. This device uses the Global Navigation Satellite System (GNSS) and encrypts data at the physical layer, making it ideal for outdoor applications. ELTRES has a receiver sensitivity of -144dB, an effective transmission rate of 80bps, and supports only unidirectional communication. However, it has an advantage over competing technologies due to its precise GNSS synchronization which enables the device to broadcast more bursts than other technologies, resulting in better system capacity, higher frequency use, efficiency, and scalability. ELTRES can utilize a total of 95625 slots across 17 channels throughout Europe thus making it more efficient than Sigfox and LoRaWAN.

Figure 1 illustrates that ELTRES comprises of two distinct components: a transmitter utilized by the user to transmit data and a receiver that receives the transmitted data. The two terminations are linked through GNSS antennas. GNSS is a technology that utilizes satellites to furnish receivers on the surface of earth with geolocation and temporal data. To clarify, GNSS antennas are employed to establish a reliable means of communication between the transmitter and receiver of ELTRES over extended distances with a maximum range of 100km and a velocity of 100km/h [15].

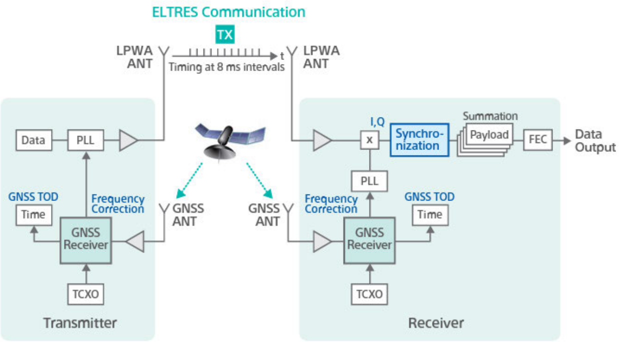

**FIGURE 1.** **Sony ELTRES communication Tx and Rx channels [15].**

The LoRaWAN standards propose the adoption of the LoRa forward error correction coding protocol, which encompasses the techniques of fragmentation and forward error correction. The LoRa communication channel is precisely designed to facilitate Line of Sight (LoS) communication for a maximum range of 15 km. Nevertheless within this particular range, it is plausible that a substantial number of parity errors may occur. The process of Error Correction Coding (ECC) involves the encoding of M symbols of data into a codeword using FEC techniques. This results in the addition of N symbols of redundancy to the codeword. This process enables the extraction of the dataword from the codeword subject to the condition that the quantity of corrupted symbols or erased data is inferior, which are customary attributes of a specific error-correcting code. FEC is a commonly employed technique in the field of telecommunications and satellite communication to improve communication reliability and throughput. Interestingly, it has also found application in LoRa technology, as reported in a study [16].

In [17], the authors provide an extensive examination of Error Correction Schemes (ECS) utilized in communication systems as well as their potential implementation in Wireless Body Area Networks (WBANs). The paper provides a comprehensive summary of the IEEE standard for WBAN encompassing crucial aspects such as channel and network models which play a pivotal role in the design and execution of Embedded Control Systems (ECS). The authors conducted analysis of multiple facets pertaining to the proposed ECS for WBAN, including the types of ECS employed, the types of WBAN utilized, the data types taken into account, and the channel types considered. The authors also investigate the measurement of reliability and the potential consideration of distinct types of reliability and delay requirements for varying data types. The authors emphasize that the existing literature fails to consider the limitations encountered by WBAN nodes in the process of designing energy conservation strategies. The potential areas of inquiry and prospects for the development and execution of energy conservation strategies in WBAN considering the limited energy resources and computational demands of nodes are proposed. In general, the paper provides significant perspectives on the obstacles and possibilities of energy conservation strategies (ECS) in WBAN and presents a beneficial structure for forthcoming investigations in this domain. The authors deduced that the forthcoming ECS for WBAN ought to be adaptable and must employ a range of ECS methodologies to manage diverse Quality of Service (QoS) requisites, latency demands, and distinct categories of nodes and channels.

The study of high-rate serially concatenated codes has been extensive owing to their capacity to attain a high coding gain and low bit error rate during data transmission over channels that are susceptible to noise. Hamming codes are frequently employed in serial concatenation as a prevalent method due to their minimal encoding and decoding complexity. In [18], the authors introduce a serially concatenated coding scheme with a high rate, which employs Hamming codes as the constituent codes. The proposed methodology has demonstrated a notable increase in coding efficiency while simultaneously preserving low bit error rate (BER) values across a broad spectrum of signal-to-noise ratios (SNRs) and code rates. The efficacy of the proposed scheme has been assessed through simulations and juxtaposed with other contemporary serially concatenated coding schemes. The findings indicate that the proposed methodology exhibits superior performance in coding gain and BER compared to alternative methodologies [18].

ECC methodology is employed to enhance the resilience of digital systems including data transfer and memory storage devices against faults. Soft errors are a potential threat to data integrity during storage or transfer processes. These errors arise from a range of factors, including radiation and electromagnetic interference can result in data corruption. The process of ECC involves the addition of supplementary data to the original information, thereby facilitating the identification and rectification of any potential errors that may arise during storage or transmission. The algorithm based on Hamming code is the prevalent form of ECC utilized in various applications. This algorithm is designed to append parity bits to the data to facilitate the detection and correction of errors because the Hamming code is a coding scheme which involves augmenting a set of eight data bits with four additional parity bits resulting in a twelve-bit code-word. The parity bits are computed based on the values of the data bits and are employed to identify and rectify any single-bit errors that might arise during the process of storage or transmission. The utilization of ECC is notably advantageous in scenarios that necessitate a heightened degree of fault tolerance such as in servers, data centers, and missions conducted in deep-space. The preservation of data integrity is of utmost importance in these applications, as any inaccuracies or mistakes may result in significant repercussions. ECC is a dependable method for safeguarding against soft errors and upholding the integrity and precision of data [19].

The trellis coding technique uses trellis coded modulation (TCM) developed by Gottfried and later implemented by Ungerboeck in 1976 when he was working for IBM. Since then, TCM has become widely acceptable for its use in various communication technologies. TCM conserves bandwidth by doubling constellation points of the signal, and combines the benefits of finite state encoding with multiple non-binary modulation. This adjustment does not have any negative consequences [20], [21] for regulating the selection of modulation signals to produce the encoded signal sequence. Once broadcasted, the signals must contend with various channel characteristics which amplify the noise in the data [21]. To decode the chaotic signals, a maximum likelihood decoder with a soft-decision nature at the receiver was employed.

In cognitive radio networks with trellis codes as component codes, authors in [22] examine the potential gains by adopting the multilevel coding scheme with huge multiple-input-multiple-output. The use of channel state information to implement beam-forming and antenna grouping in spacetime coding based on multi-level QAM signaling and beam-forming is for use in cognitive radio to mitigate the impact of primary users and allows secondary users to operate. In this system, primary users allocate channels to secondary users dynamically, and the transmission relies on signals that use quadrature amplitude modulation and an adaptive grouping of antennas with weights optimized based on the secondary user's resource allocation. The results indicate that this coded system achieves low bit, symbol and frame error rates with the signal-to-noise ratio being affected by the sensing time of the sources.

Table 1 provides a summary of different research papers related to the application of LPWAN and wireless communication technologies in various fields. The table includes the reference number, contribution, and research gaps being left unaddressed by each paper. The contributions of these papers include proposing a hybrid backhaul communication architecture for intelligent transportation systems, evaluating the performance of LPWAN technologies in IoT-based smart farming, identifying the subcategories of smart cities where LoRa-based IoT solutions have been implemented, comparing leading LPWAN technologies and offering a new approach for IoT connectivity using LPWANs, proposing a new information infrastructure called the Internet of Energy Things (IoET) based on LPWAN technology, achieving high data rate communication for LPWAN, developing wireless communication technology which can enhance wireless coverage in Non-Line-Of-Sight (NLOS) environments, recommending a wireless system that deterministically uses reflection waves on RPW, and developing the ELTRES technology to enable long-range, low-power communication for IoT devices.

The research gaps that are not being addressed by these papers include a nonexistence of efficient backhaul communication for intelligent transportation system (ITS) using LPWAN, an absence of extensive study on the suitability of LPWAN technologies for remote communication in IoT-based smart farming, a lack of a macro-plan for the development of a sustainable city using LoRa-based IoT solutions, a dearth of high data rate modulation schemes for LPWAN communication, a need for a wireless

**TABLE 1.** Summary of contributions and research gaps in identified in literature for error detection and correction codes.

| Ref. No. | Contribution | Research Gaps Identified |
|---|---|---|
| [2] | Proposed a hybrid backhaul communication architecture using LPWAN to improve the reliability and efficiency of ITS | Absence of efficient backhaul communication for ITS using low-power wide area networks (LPWAN) |
| [3] | The paper evaluated the performance of two LPWAN technologies, LoRaWAN and Sigfox, in terms of their suitability for remote communication in IoT-based smart farming. | The suitability of LPWAN technologies for remote communication in IoT-based smart farming has not been extensively studied. |
| [4] | Identifies the subcategories of smart cities where LoRa-based IoT solutions have been implemented, including agriculture, energy, environment, healthcare, industry, traffic, and waste management. | Macro-plan for the development of a sustainable city using LoRa-based IoT solutions and security aspects, such as response to security attacks and vulnerability policies need to be addressed. |
| [8] | Overview of technical differences and comparison of leading LPWAN technologies (Sigfox, LoRaWAN, NB-IoT) and introduction of a new approach for IoT connectivity using LPWANs. | Absence of efficient connectivity solutions for IoT devices and need for low-cost connectivity for large number of low power devices in IoT |
| [9] | Proposed a new information infrastructure called the Internet of Energy Things (IoET) based on LPWAN technology for making DSM practicable. Compares NB-IoT and LoRa technologies with GPRS and area IoT technology. Proposes a wireless-to-cloud architecture for the IoET. | Existing information infrastructure is designed for centralized systems which does not meet demand-side management (DSM) requirements. |
| [11] | Achieved high data rate communication for M2M LPWAN | Absence of high data rate modulation schemes for M2M LPWAN communication to address the need for higher data rate communication for M2M LPWAN applications |
| [12] | Developed first transceiver adopting the Rotating Polarization Wave (RPW) scheme,and proposed a demodulation method to efficiently receive RPW signals. | Need for a wireless communication technology that can enhance wireless coverage in Non-Line-Of-Sight (NLOS) environments. |
| [13] | Proposed a wireless system that deterministically uses reflection waves on rotating polarization wave (RPW). | Lack of deterministic polarization communication in wireless systems resulting in deteriorated signal quality |
| [15] | Sony developed the ELTRES technology, which uses a combination of Bluetooth Low Energy (BLE) and proprietary wireless communication protocols to enable long-range, low-power communication for IoT devices. The technology also includes a feature for detecting and avoiding interference from other wireless devices. | There is a need for a low-power, low-cost wireless communication technology that can support IoT devices over long distances, especially in areas with poor network coverage. |

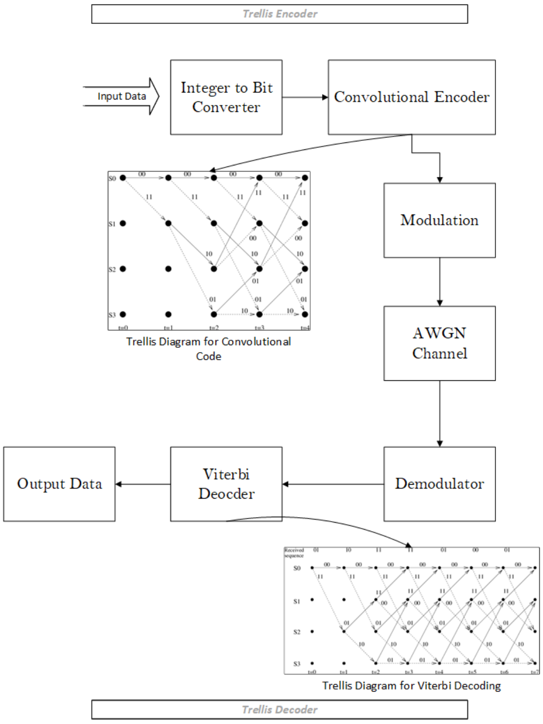

**FIGURE 2.** TCM structure of encoder and decoder.

communication technology that can enhance wireless coverage in NLOS environments, a lack of deterministic polarization communication in wireless systems resulting in deteriorated signal quality, and a need for a low-power, low-cost wireless communication technology which can support IoT devices over long distances, especially in areas with poor network coverage.

Convolution coding is the basic method, with coding rate n/(n+1). Figure 2 illustrates a typical structure of TCM encoder and decoder in a communication system. TCM derived its name from the idea of tree or trellis coding. The fundamental property of trellis codes is based on the idea of signal-set partitioning. This adds redundant coding in the signal space [21] for Convolutional coder does not encrypt every bit.

This paper provides a review on the ECC techniques in the LPWAN networks and IoT applications. Section I provided the detailed introduction to the LPWAN technologies in conjunction with the ECC and FEC based comparisons in LPWAN technologies, section II of this paper discusses the ECC for sundry wireless applications with particular focus on LoRaWAN. Section III reviews the ECC in IoT applications along with the review of ECC in Wireless Sensor Networks. Section IV offers analysis of results and discussion of literature under consideration while the section V provides the conclusion to this paper.

## II. ERROR CORRECTION CODING

The dependability of data transmission holds significant importance in contemporary communication systems. The transmission of data in wireless communication is susceptible to diverse forms of interference and noise leading to potential errors in the received data. Consequently, ECCs are employed to guarantee dependable transmission of information. Several forms of ECCs have been suggested such as Turbo, Convolutional, low-density parity-check, and Polar codes. The selection of ECC is contingent upon a multitude of factors including the preferred degree of dependability, intricacy, and computational assets at hand. The study in [23] conducts a BER analysis of Convolutional, Turbo, low-density parity-check (LDPC), and Polar codes across varying channel conditions with the aim to determine the most effective ECC for ensuring dependable wireless communication. The survey discusses a high-rate irregular LDPC codes that exhibit efficient encodability for moderate-length applications. The proposed codes exhibit an irregular structure, which yields superior performance compared to LDPC codes with a regular structure. The employed methodology in the design incorporates a belief-propagation decoding algorithm and a quasi-cyclic construction, resulting in a high-rate code which exhibits commendable performance. The suggested codes exhibit a reduced encoding complexity while being capable of attaining a code rate of 0.96 for a block size of 1032 bits. The outcomes of the simulation documented in [24] demonstrate that the proposed codes exhibit commendable efficacy and can attain a bit error rate in close proximity to the Shannon limit. The codes possess the potential to be employed in diverse applications including but not limited to wireless communication systems, storage systems, and digital broadcasting systems. These applications require codes with high rates, alongside encoding and decoding of low complexity.

The paper [25] provides a review of various ECCs used for short-length transmissions. The authors highlight the importance of ECCs in modern communication systems and identify the need for efficient codes that can correct errors with minimum redundancy. The paper compares the performance of several ECCs including repetition codes, Hamming codes, BCH codes, Reed-Solomon codes, and LDPC codes for different block sizes and error rates. The results show that the choice of ECC depends on the required error-correction capability, block size, and computational complexity. The LDPC codes provide a good trade-off between error-correction capability and complexity for short-length transmissions while Reed-Solomon codes are more suitable for longer blocks. Added to this, the review provides insights into the performance of different ECCs and can aid in the selection of appropriate codes for short-length transmissions in various applications.

The [26] provides a thorough analysis of the challenges associated with error correction in LPWANs and provides an overview of the various ECC techniques that have been proposed to address these challenges. The authors provide a background on LPWANs and the unique challenges associated with error correction in these networks, including low data rates, low power constraints, and large distances between nodes. The various ECC techniques which have been proposed for LPWANs including Block codes, Convolutional codes, Turbo codes, and LDPC codes were comprehensively surveyed.

### A. A SOFTWARE SYSTEM FOR HIGH THROUGHPUT AND LOW LATENCY DATA TRANSFERS IN WIDE-AREA NETWORKS

The software system UDT+FEC addresses the various issues related to the network performance in high bandwidth-delay product (BDP) networks, and offers special benefits for transferring large amounts of data over wide-area networks (WAN), as suggested in [27]. This system uses the 2D-XOR FEC extension of UDT (user data-gram protocol) to achieve comparable throughput and latency with other advanced tools. Moreover, UDT+FEC offers the advantage of lower variance in message arrival times at the receiver. The relative benefits of UDT+FEC were assessed by comparing it with GridFTP coupled with CUBIC, BBR, and parallel streams, using different benchmarks. It was found that UDT+FEC exhibits significantly less volatility in message delay arrival time as measured by message inter-arrival times in one-way transmissions [28].

The article referenced as [29] delineates a novel methodology which employs FEC to enhance the dependability of wireless transmission in industrial settings utilizing WSN compliant with the IEEE 802.15.4 standard. The technique under consideration enables the involvement of non-FEC coded nodes in the network while simultaneously guaranteeing the prevention of transmission of erroneous packets. Because of this phenomenon, there is a rise in dependability, a decrease in the quantity of re-transmissions, and a reduction in the mean packet latency. The technique under consideration is in alignment with the IEEE 802.15.4 standard and can be executed on current platforms without necessitating any involvement from chip manufacturers or standardization organizations. The proposed scheme was assessed in both link and network-level scenarios. The results indicate a significant increase in packet delivery rate ranging from 21% to 56% when compared to uncoded transmissions. The proposed methodology yields commensurate Packet Delivery Ratio (PDR) performance as the conventional FEC scheme, albeit with substantially reduced computational burden for decoding and concentrates on enhancing the implementation of the FEC code to achieve greater efficiency. In general, the article offers a pragmatic and efficient strategy for enhancing the dependability of WSN transmissions within industrial settings.

### B. LORAWAN PHYSICAL LAYER DESIGN AND PERFORMANCE ANALYSIS

The LoRaWAN protocol is a popular IoT protocol. It uses a unique spread spectrum modulation technique based on chirp modulation and incorporates channel coding, whitening, gray mapping, and interleaving. The protocol supports a variety of spreading factors and coding rates allowing it to operate in a wide range of signal-to-noise ratios. Reverse engineering attempts have revealed some specifics of the LoRa physical layer [30]. The LoRa protocol uses spread-spectrum frequency modulation with $N = 2^{SF}$ chips per signal and a bandwidth of B, where SF stands for spreading factor (SF). Gray mapping is used to translate SF bits into symbols which are then carried by each LoRa symbol. The carrier frequency and additive white Gaussian noise offset the performance of LoRa system resulting in a coded frame error rate. Initially, two methods were developed to estimate the FER of LoRa frames which have been coded under additive white Gaussian noise (AWGN). The unique combination of Gray mapping, interleaving, and coding makes LoRa highly resistant to small residual carrier frequency offset (CFO) values. Furthermore, a simplified method for approximating the LoRa FER in the presence of CFO was created [31].

New coding scheme called low-density parity check coding scheme for LoRa networks to improve the reliability of data transmission is proposed by the researchers in [32]. A Low-Density Parity Check Coding Scheme for LoRa Networks for LoRa (LLDPC) is a LDPC code which uses a sparse parity-check matrix to achieve a high code rate while maintaining low decoding complexity. The proposed scheme is designed specifically for LoRa modulation which has unique characteristics such as long transmission time, and low signal-to-noise ratio. The performance of LLDPC is evaluated through simulations and compared with other existing coding schemes for LoRa, and the results show that the LLDPC outperforms them in terms of BER and packet error rate (PER) under various channel conditions. The authors also provide a detailed analysis of the LLDPC code design and decoding process, which can serve as a useful reference for future research in this area. Overall, the proposed LLDPC coding scheme has the potential to improve the reliability and efficiency of LoRa networks, which can be beneficial for various applications such as IoT and smart city systems.

### *C. ITERATIVE IDENTIFICATION AND DECODING IN LORAWAN PHYSICAL LAYER*

The article [33] introduces a concatenated coding scheme which utilizes Hamming codes and accumulator codes in conjunction with high-order modulations to attain rapid decoding. The proposed methodology has been formulated to enhance the balance between the intricacy of decoding, the efficacy of error correction, and the rate of code. The efficacy of the proposed scheme was assessed to validate an optimal balance between error-correction performance and decoding complexity. This renders it highly suitable for high-speed communication systems. Based on the findings, the suggested approach exhibits superior performance in comparison to other concatenated coding techniques presently accessible, with respect to both decoding intricacy and error correction efficacy. The scheme presents a viable resolution for attaining rapid decoding in communication systems while simultaneously upholding the robust error-correction capabilities.

The article referenced as [34] presents a novel approach for handling binary data streams of higher rates through the utilization of a coding-and-modulation technique. The proposed methodology entails partitioning of the input bit sequence into multiple bit sequences which are concurrently subjected to an outer Hamming code with a high rate and an inner two-state rate-1 accumulator code. The resulting bit streams are interleaved and subsequently converted into symbols that are transmitted using higher-order modulation. The novelty of this methodology is attributed to the fusion of Hamming and accumulator codes with multiple constituents along with the concurrent structures of the encoder and decoder circuits. The utilization of this methodology facilitates concurrent processing, thereby empowering the encoder and decoder to manage information at a pace that surpasses the capability of singular encoder and decoder circuits. The method under consideration presents a notable benefit in terms of providing parallel processing capabilities to enable rapid encoding and decoding operations. This renders it a viable option for handling binary data streams with high data rates.

LoRaWAN is a widely adopted IoT protocol for utilization in the physical layer for long-range wide-area networks. The physical layer of networks has been the subject of a recent article [35] proposing a novel approach that employs an iterative identification and decoding (IDD) technique in conjunction with a blind channel estimator. The proposed methodology involves the exchange of log likelihood ratios (LLRs) as soft decision values between the LoRa demodulator and the Hamming decoder. This approach aims to enhance the detection capabilities of the signal while simultaneously achieving iterative gain. Conventional demodulation and decoding techniques employed in LoRa networks rely on hard decision values which are binary in nature to detect the received signal. Nonetheless, this leads to a reduction in mutual information which significantly hinders performance. The methodology aims to account for the stochastic nature of both input and output values of the demodulator and decoder as a mean of addressing the issue at hand. The article examines the signal model of Hamming code and LoRa, in addition to the modulation and demodulation techniques employed in LoRa systems to develop a multidimensional signal model for the received signal. The model for coherence detection is based on Bit-Interleaved Coded Modulation with Iterative Detection and Decoding (BICM-IDD) and involves iterative swapping of the LLR between the demodulator and the decoder. The soft decision output of the demodulator is determined by the signal model which indicates that LLR is the derived value. Subsequently, a comparison was made between coherent and non-coherent detection techniques utilizing the proposed blind channel estimator coherent detection approach. The research findings indicate that the BICM-IDD model with coherent detection outperforms the model with non-coherent detection, even when the symbol count is either 4 or 32, in terms of BER performance. The study confirmed that an increase in the coherent detection symbol count could result in an improvement in the accuracy of the estimation of the fading coefficient. In general, it is anticipated that this methodology will enhance the efficacy of LoRa networks by attaining superior bit error rate performance and precision in the estimation of the fading coefficient. The methodology constitutes a noteworthy addition to the realm of IoT due to its potential to enhance the dependability and efficacy of Long Range (LoRa) networks which can be more adaptable to a diverse array of used cases [35].

### *D. LORAWAN NETWORKS AND THE CCARR TECHNIQUE FOR QOS ENHANCEMENT*

When deploying transmissions over low power wide area networks like LoRa, PER and time on air are two important

**TABLE 2.** The contributions and identified research gaps for error correction codes in sundry wireless communication applications.

| Ref. No. | Contribution | Research Gaps Identified |
|---|---|---|
| [16] | LoRaFFEC protocol enabled fragmentation and Forward Error Correction | Absence of satisfactory Data Delivery Rate (DDR) for LoRaWAN deployments with varying packet losses |
| [17] | This paper surveys different ECS used in communication systems, summarizes IEEE standard and network models for WBAN,conducts a review of ECS proposed for WBAN,and identifies future challenges for ECS design. | The current literature on ECS for WBAN does not utilize the constraints faced by WBAN nodes during ECS design. |
| [19] | Use of Cell Design Methodology (CDM)for optimization of ECC | Lack of emphasis on the impact of using CDM logic style on other performance parameters such as area, complexity, and error correction capability. |
| [22] | Proposes the use of multilevel coding scheme with trellis codes as component codes and massive MIMO in Cognitive Radio Networks to improve spectral efficiency andlow decoding complexity. | Error-correcting codes with minimal error constraints for wireless need to be explored. communications. |
| [23] | Documents performance of different high-performance error-correcting codes, including Convolutional, Turbo, LDPC, and Polar codes, in terms of BER for various scenarios ranging from reliable to high-throughput data transmission. | Paper does not investigate the effect of varying channel conditions or the impact of the signal-to-noise ratio (SNR) on the performance of the different coding schemes |
| [24] | The paper proposes a new design for moderate-length high-rate irregular LDPC codes that can be encoded efficiently. | Paper does not investigate the performance of the proposed codes under different channel conditions, which could affect their error-correcting capabilities |
| [26] | The paper presents an expression for critical distance and shows that analog the decoders are the most energy-efficient ECC solution for certain WSN environments and applications. | Need to determine energy efficiency of specific ECC implementations in WSNs in different environments, frequencies, and decoder types. |
| [28] | The paper presents UDT+FEC, a software system that uses 2D-XORforward error correction to provide high throughput, low latency, and low-variance latency on wide-area networks, while also identifies future work to optimize the implementation and its evaluations under different conditions. | Need for a system to provide high throughput, low latency, and low-variance latency on WAN, especially for large data transfers, using forward error correction. |
| [29] | The proposed FEC-based approach provides improved reliability, reduced retransmissions, and lower average latency, while maintaining identical PDR performance to the traditional FEC scheme with significantly reduced decoding function calls. | The impact of varying wireless channel conditions on the proposed FEC-based approach is not explored. |
| [30] | The paper considers different coding rates and spreading factors and provides insights into the impact of these parameters on the error-correcting performance of the LoRa coded frames. | The paper does not discuss the practical implications of the results for the design and deployment of LoRa-based LPWANs. |
| [31] | The paper provides a theoretical analysis of the SER performance of LoRa systems under non-aligned interference, which can be useful in designing and optimizing LoRa-based communication systems for the IoT. | The paper does not investigate the impact of non-ideal channel conditions, such as fading and shadowing, on the SER performance of LoRa systems under non-aligned interference. |
| [33] | The paper proposes a concatenated coding scheme which combines Hamming codes and accumulator codes with high-order modulations for high-speed decoding. | The paper does not investigate the impact of non-ideal channel conditions, such as fading and noise, on the performance of the proposed concatenated coding scheme. |
| [35] | The paper proposes an iterative demodulation and decoding scheme with a blind channel estimator for LoRa modulation,to improve the performance of LoRa networks in terms of bit error rate and packet error rate (PER). | Comparison with other state-of-the-art demodulation and decoding methods for LoRa modulation in terms of performance and complexity is direly needed. |

features for both applications and operators in the IoT. For LoRaWAN networks, the channel coding strategy seeks to enhance these Quality of Service (QoS) features. The channel coding adaptive redundancy rate (CCARR) technique divides subsequent frames into segments and employs Reed-Solomon FEC. The level of FEC overload is dynamically controlled by completion acknowledgments. Using a probabilistic methodology, potential gain of CCARR was determined. The protocol has a significant PER gain over LoRaWAN with a regulated time on air increase through improved FEC overload, according to simulations in [36] and off-the-shelf test bed trials.

The table 2 summarizes various research papers that propose solutions for improving the performance of wireless communication systems along-with their pitfalls as research gaps. The LoRaFFEC protocol proposes fragmentation and forward error correction to improve data delivery rate for LoRaWAN deployments with varying packet losses. However, the literature on ECCs for wireless communication systems does not utilize the constraints faced by wireless body area network (WBAN) nodes during ECC design, due to lack of emphasis on the impact of using cell design methodology logic style on other performance parameters. Other papers propose the use of multilevel coding schemes and massive MIMO in cognitive radio networks, explore the energy efficiency of specific ECC implementations in wireless sensor networks, and propose FEC-based systems which can provide high throughput and low latency on wide-area networks. However, the impact of varying wireless channel conditions on these proposed solutions in connection to a lack of comparison with other state-of-the-art demodulation and decoding schemes for LoRa modulation needs to be explored.

From Figure 3, it can be observed that LoRaWAN uses a star-of-stars topology in which a limited number of operational gateways always act as secure message relays to connect many battery-powered end devices with a central network server at the back end. It can be observed that there is no direct connection between a particular gateway and the end devices. Consequently, when an end device sends a frame, it is typically received by multiple gateways, which then forward it to the network server. The network server is responsible for various functions such as application delivery, duplicate elimination, and communication protocol selection [37].

Wired ethernet was used to link the gateway to the internet. The Things Networks11 (TTN11), a network server which implements LoRaWAN requirements, was accessible due to this internet connection with no influence over how this cloud server behaved, particularly its internal strategy which conducts down-link broadcasts utilizing a small spreading factor and the highest down-link permitted power. Therefore, during the testing, this acknowledgment channel was lossless. It is important to note that the CCARR protocol benefits from receiving 100% of its completion acknowledgments as compared to the simulated environment. The acknowledgment's time on air (TOA) was a tenth of the up-link frame's TOA with test bed experimental configuration, as shown in Table 4, while utilizing a high spreading factor to produce contentions.

**TABLE 3.** Review of error correction codes for IoT applications.

| Ref. No. | Contribution | Research Gaps Identified |
|---|---|---|
| [36] | The paper proposes a channel coding scheme to improve the QoS in LoRa (Long Range) networks. The proposed coding scheme is based on LDPC codes and is optimized for LoRa networks. | The paper does not discuss the practical implications of the results for the deployment of LoRa networks in real-world applications, particularly in the context of IoT and smart city applications. |
| [39] | The paper presents a new method for designing LDPC codes which are within 0.0045 dB of the Shannon limit. | Paper does not provide a detailed analysis of the trade-offs between coding gain, complexity, and energy efficiency, which are critical considerations in the design of communication systems. |
| [40] | The paper presents a new method for designing non binary irregular LDPC codes that can achieve near-Shannon limit performance with linear-time encoding. | The paper does not provide a detailed analysis of the trade-offs between coding gain, complexity, and energy efficiency, which are critical considerations in the design of communication systems. |
| [41] | The paper proposes an error correction code called LCPC (Layered Concatenated Parity Check), which is specifically designed for IoT applications with low-power and resource-constrained devices. | Need for an error correction code which can be optimized for IoT applications to can provide reliable communication with low-power and resource-constrained devices. |
| [42] | The paper proposes an energy-efficient and adaptive channel coding approach for NBIoT systems, to improve the energy efficiency and reliability of communication. The proposed approach utilizes a combination of Convolutional code and Polar code for error correction, and dynamically adjusts the coding rate and power allocation based on the channel conditions. | Investigating the scalability and robustness of the proposed approach for large-scale IoT systems with varying channel conditions and interference levels can be another potential research direction. |
| [43] | The paper presents a novel SEC based on CDM logic style to reduce power consumption and increases energy efficiency in IoT devices. The proposed SEC only corrects single errors in the data. | The proposed SEC only corrects single errors in the data. Extending the SEC to correct multiple errors in the data, for IoT applications requiring higher levels of error correction can be investigated. |

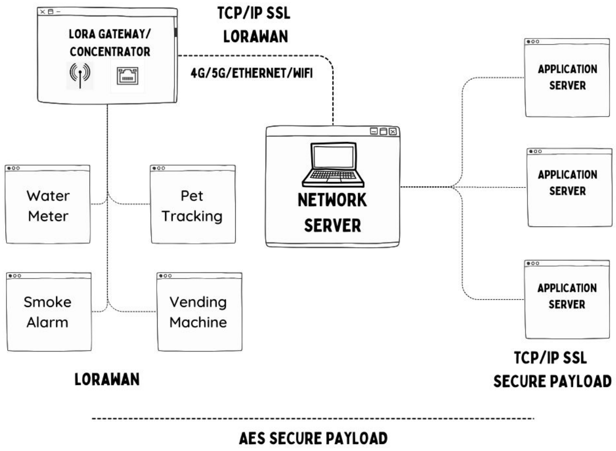

**FIGURE 3.** Networking architecture of LoRaWAN [37].

**TABLE 4.** TOA of frames from experiments in [36].

| Link | SF | TOA (ms) | Payload (Bytes) |
|---|---|---|---|
| UP | 12 | 1646.6 | 16 |
| Down | 9 | 164.9 | 2 |

The authors in [37] discuss the CCARR protocol used to improve the QoS of LoRa LPWAN technology. The protocol achieves this by using FEC in the form of Reed-Solomon codes, which allows for high packet delivery rate over lossy channels while imposing minimal network overhead. The CCARR protocol is found to provide higher packet rate (PDR) with lower transmission TOA when compared to the current approach used in LoRaWAN. In addition, CCARR has an advantage over other protocols like SRR and DaRe for being able to self-regulate based on the quality of the channel it is operating on. The CCARR protocol dynamically controls FEC overload based on the completion acknowledgments it receives which is particularly effective for ALOHA access networks such as LoRa. Consequently the overall network capacity of LoRaWAN is increased by decreasing FEC TOA. In a nutshell, the CCARR protocol is a promising option for enhancing the QoS of LoRa LPWANs due to high PDR with minimal network overhead and the ability to adapt to different channel conditions. This makes it an attractive option for operators and applications in the IoT.

Table 3 discusses and covers a wide range of topics related to IoT with a focus on channel coding and error correction techniques. The contributions include the design and analysis of various coding schemes such as LDPC, Turbo, Hamming, Polar, and Low Complexity Parity Check (LCPC) codes as well as the investigation of their performance under different scenarios. Additionally, several papers propose new approaches to improve the energy efficiency and adaptability of channel coding in IoT systems. However, the research gaps identified in many of reported approaches need a deeper understanding and real-world validation for their scalability and robustness in large-scale IoT deployments. Overall, they provide valuable insights into the challenges and opportunities for channel coding in IoT applications.

The ECC taxonomy shown in Figure 4 is a significant resource to comprehend and classify ECCs in the field of communication systems, particularly in relation to their significance within the domain of LPWAN technology. The significance of ECCs cannot be overstated within the dynamic and rapidly changing area of wireless communication. These codes play a crucial role in improving the integrity and dependability of data transmission and reception particular in low-power, and long-range LPWAN systems. At the top of the taxonomy, three fundamental categories are presented which lay the foundation of ECCs: Block codes, Reed-Solomon codes, and Convolutional codes. Each of the categories is specifically designed to address the specific requirements and limitations faced by wireless communication systems. The Block codes include ECCs such as Hamming, BCH (Bose-Chaudhuri-Hocquenghem), and Golay. These codes have distinguished features to rectify faults inside a block of data for very ideal situations wherein data are structured into segments of defined length. One example of an ECC is the Hamming code notable for

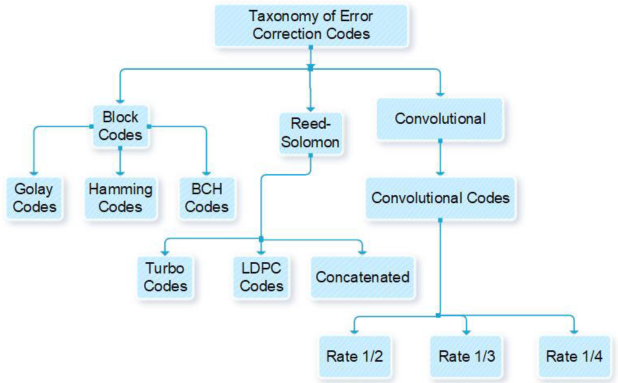

**FIGURE 4.** **Taxonomy of error correction codes.**

its simplicity and effectiveness. This ECC corrects single errors and detects double errors in LPWAN applications that prioritize simplicity and efficiency. The Reed-Solomon codes are generally acknowledged for effectively rectifying errors that occur in bursts and guarantee the accuracy of data in various applications. In the context of LPWAN, the utilization of Reed-Solomon codes is carried out to mitigate any errors that may occur due to the presence of noise and interference during the transmission of data over long distances. Convolutional codes have a substantial significance in error correction. They can be broken into smaller segments to fit various code rates (1/2, 1/3, 1/4), which demonstrates their versatility and adaptability. Convolutional codes having a transmission rate of 1/2, for example, convey one unit of valuable information for every two units transmitted. This characteristic renders them highly effective in situations where constraints on available bandwidth exist. On the other hand, codes that have a rate of 1/4 exhibit a trade-off between efficiency and improved error correcting capabilities. Convolutional codes with variable constraint lengths such as 3, 5, and 7, are designed to accommodate diverse channel characteristics and error patterns. It is worth mentioning that the parameter constraint length must be noticed when examining them. The codes adapt to error correction procedures based on the particular circumstances for guaranteeing reliable transmission of data even in adverse settings. Concatenated codes are regarded as a highly advanced method for error correction. The Turbo codes repair errors by exploiting the capabilities of many constituent codes operating in conjunction, resulting in exceptional dependability in the transfer of data. The integration of Reed-Solomon codes with other codes introduces an additional level of adaptability in the development of error correction strategies for LPWAN networks. Ultimately, the implementation of appropriate ECCs contributes significantly to the effectiveness and accomplishment of various IoT and Machine-to-Machine (M2M) applications that heavily depend on LPWAN connectivity.

## III. ECC FOR IOT APPLICATIONS AND WIRELESS SENSOR NETWORKS

The use of LDPC codes is the basis of the error correction scheme proposed in [42]. These codes are known for their ability to correct errors and consume less power. The simulations are performed to evaluate the performance of proposed scheme in terms of energy consumption and error rate. The performance of error correction scheme stands out when compared with the performance of other existing error correction schemes by demonstrating significant improvement of energy efficiency and error rate. The trade-offs between energy consumption and error rate provide valuable insights into error correction in LPWANs in IoT sensors. Additionally, the paper is relevant to current research in the field of LPWANs for IoT sensors. The authors emphasize on the importance of low-power error correction for the deployment of LPWANs for IoT sensors and discuss the potential benefits of their proposed scheme in terms of network deployment and cost, highlighting the practical implications of their work.

The utilization of channel coding is a crucial method employed in communication systems to enhance the dependability of data and augment its resilience against noise and interference. Multiple error detection and correction codes are at disposal such as Hamming, Reed Solomon (RS), Bose-Chaudhuri-Hocquenghem (BCH), and low-density LDPC codes. Each of the codes possesses distinct characteristics which render it appropriate for deployment as a channel coding mechanism in a communication network. The Hamming code is an effective and uncomplicated coding scheme capable of rectifying single-bit errors in data transmission. Reed-Solomon codes are frequently employed in satellite communications owing to their superior error-correcting proficiency and ability to rectify burst errors. BCH codes extends the Reed-Solomon (RS) codes.

In addition BCH codes are renowned for correcting multiple errors. In recent years, LDPC codes have gained considerable interest due to their exceptional error-correcting capabilities, which approach the theoretical limit established by Shannon. LDPC codes exhibit a reduced level of complexity in both encoding and decoding processes, thereby enabling them to achieve substantial coding gains when implemented with extended codewords. Optical communication, wireless communication, and storage systems are among the communication systems where they find application. LDPC codes have garnered significant attention in recent years due to their appealing characteristics, and numerous methodologies have been suggested to enhance their efficacy. In general, the utilization of diverse error detection and correction codes is essential for guaranteeing dependable and protected communication. LDPC codes have demonstrated significant potential by virtue of their exceptional error-correction capabilities and minimal encoding and decoding complexity. It is probable that the reliability and performance of communication systems will be enhanced in the future

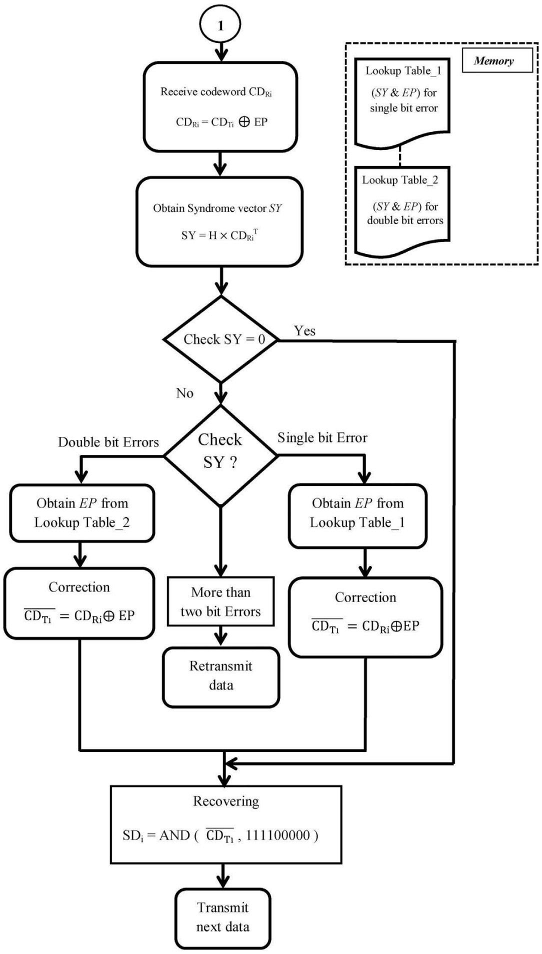

**FIGURE 5.** Error detection and correction flow chart for LCPC codes [41].

through the implementation of more sophisticated error correction techniques as a result of ongoing research and development [38].

The Hamming codes a venerable method for detecting and correcting errors, possesses the capability to rectify exclusively single bit errors while being able to detect up to double bit errors. The scarcity of readily identifiable symptoms poses a challenge in remedying errors made in double-entry bookkeeping. The parity check matrix H of the Hamming code (7, 4) comprises 3 rows and 7 columns results in 8 syndrome values, as reported in [39] and [40]. Figure 5 depicts the flowchart pertaining to single bit and double bit errors in the LCPC code as observed at the receiver end. The proposed code assumes the presence of two lookup tables namely errors patterns (EP) and syndrome vector (SY), which are utilized for the detection of single and double bit errors, and are stored in the memory of the system. After the codeword is received, the initial step involves performing error detection for codeword received($CD_{Ri}$) on the receiver side. The syndrome vectors (SY) value is determined at the error detection unit. The type of error (i.e., single or double bit errors) and location of the bit error in $CD_{Ri}$ determines the value of SY. The EP may then be derived using the lookup tables kept in memory depending on the SY value.

The low complexity parity check codes represent a novel collection of techniques for detecting and correcting errors. They are capable of identifying and rectifying bit errors which occur both consecutively and non-consecutively. The codes serving as a FEC mechanism exhibit compatibility with WSNs and IoT applications. In comparison to LDPC and Reed Solomon (RS) codes, LCPC codes exhibit lower complexity and demand reduced memory resources. In contrast to LDPC codes, LCPC codes exhibit greater efficiency as they do not require iterative decoding procedures. Furthermore, the simulations demonstrate that the LCPC codes under consideration exhibit superior performance compared to Hamming, RS, and LDPC codes while simultaneously preserving a minimal degree of computational complexity. The utilization of LCPC codes is highly advantageous for numerous emerging IoT applications due to the reduction in battery consumption because of decreased frequency of re-transmissions, as cited in [41].

The LCPC algorithm for error detection and correction was introduced by researchers in [41]. The efficacy of the proposed LCPC codes utilizing BPSK modulation over the AWGN channel is examined. The analysis of the suggested LCPC codes is conducted with respect to their BER performance in comparison to Hamming, Reed-Solomon, Bose-Chaudhuri-Hocquenghem, binary and non-binary LDPC codes. The results indicate a noteworthy enhancement in the BER performance of the LCPC code in comparison to established codes such as LDPC, RS, BCH, and Hamming codes. In comparison to LDPC codes, which necessitate over 20 iterations for error codeword correction, LCPC codes exhibit distinctive features which distinguish them from LDPC codes. These include encoding and decoding of low complexity, minimal memory requirements for matrix multiplication in instances of large codeword sizes, and the absence of iterations. The results obtained from the evaluation of the BER performance of the LDPC code indicate that it is more suitable for implementation in IoT and WSN applications.

### A. ENCODING DATA IN NARROWBAND IOT

A novel channel coding scheme has been proposed by researchers in [42], which utilizes adaptive coding and modulation (ACM). The proposed scheme employs adaptive coding rate and modulation scheme in response to the channel conditions to attain superior energy efficiency and reduced error rates in contrast to conventional fixed coding and modulation schemes. The researchers conducted comprehensive simulations to assess the efficacy of their proposed methodology and contrasted it with various other existing channel coding methodologies.

A comprehensive examination of the issue of energy efficiency in NB-IoT systems is carried out to suggest a viable remedy involving the utilization of ACM. The outcomes of the simulations demonstrate that the suggested methodology yields noteworthy enhancements in energy efficiency and reduction in error rate when compared to the current schemes. This underscores the potential advantages of the proposed approach. One input related to its pertinence to contemporary investigations in the domain of NB-IoT systems. The significance of energy-efficient channel coding is emphasized in the context of NB-IoT system implementation. This is particularly relevant given the increasing need for low-power and cost-effective wireless networks to cater for the demands of IoT applications. The authors engage in a discourse regarding the potential advantages of their suggested approach in relation to network implementation and expenses, thereby underscoring the pragmatic ramifications of their research.

In article [54], an innovative NB-IoT energy-efficient adaptive channel coding (EEAC) technique is presented. The primary objective of the study is to augment the energy efficiency of Narrowband Internet of Things (NB-IoT) systems while taking into account the prevailing channel conditions. The proposed scheme exhibits dynamic selection of an appropriate channel coding scheme to take into account the estimated channel conditions. Additionally, the scheme minimizes the number of transmission repetitions. The link-level simulations showcased in [54] exhibit superior performance of the energy-efficient adaptive channel coding (EEACC) scheme in comparison with current methodologies with regard to energy efficiency, reliability, latency, and scalability.

The article [55] introduces a Turbo channel coding algorithm designed for the up-link transport channel within NB-IoT systems. The methodology involves the implementation of a cyclic redundancy check syndrome calculator with a bit length of 24 and the utilization of Turbo codes alongside a Convolutional encoder with a tail bit. This study centers on the identification and rectification of errors to enhance the quality of signals through evaluation of performance and on simulations utilizing NB-IoT specifications. The study demonstrates the capacity of the algorithm to attain favorable outcomes with minimal decoding iterations in addition to a low BER. The papers [54] and [55] discuss distinct facets of channel coding within NB-IoT systems. The primary objective of the EEACC scheme, as presented in [54] paper, is to enhance energy efficiency through the dynamic selection of suitable channel coding schemes and the reduction of transmission repetition which are contingent upon channel conditions. The focus is on the dependability of the network, the time data take to travel through the network, and the ability of the network to expand in size and capacity. In [55] the execution of a distinct Turbo channel coding algorithm for the purpose of detecting and rectifying errors in the up-link transport channel is reported. The paper underscores the benefits of employing Cyclic Redundancy Check (CRC) for error detection and FEC for error correction. In [54] a systematic methodology which utilizes link-level simulations to authenticate its efficacy is presented at first, while the subsequent manuscript centers on simulation and evaluation of the Turbo channel coding algorithm. The papers [54] and [55] make a valuable contribution to the NB-IoT channel coding domain by identifying and tackling particular obstacles, as well as presenting potential remedies. The paper [54] presents evidence for the superior efficacy of the EEACC scheme in comparison to existing methodologies. In contrast, the paper [55] exhibits the Turbo channel coding algorithm's performance in accordance with NB-IoT prerequisites. The primary focus of the [54] paper is on the incorporation of energy efficiency and adaptability within channel coding whereas [55] places its emphasis on the utilization of a turbo channel coding algorithm for the purpose of error detection and correction. Both papers offer significant contributions to the domain of channel coding in NB-IoT systems and offer valuable insights for enhancing the overall communication performance and dependability of such systems.

### *B. OPTIMIZING SINGLE ERROR CORRECTION CODES FOR ENERGY EFFICIENCY WITH CELL DESIGN METHODOLOGY*

The increasing miniaturization of technology has resulted in an ever increasing need for single error correction encoders and decoders to ensure low power consumption, high speed, and optimal utilization of space and energy resources. The employment of Single Error Correction (SEC) is deemed essential for a wide range of applications, including but not limited to IoT devices, memory storage, and security applications. Numerous studies have been carried out to develop efficient ECC to cater for the requirements of energy conservation and cost-effectiveness. The Cell Design Methodology (CDM) is an approach utilized to enhance the performance of Single Electron Transistors (SECs) at the transistor level. The objective is to enhance the efficacy of SEC codes regarding power and energy utilization. This research endeavors to analyze and contrast the power and energy consumption of SEC codes which have been executed through conventional CMOS (C-CMOS) and CDM logic architectures. The findings in this paper detail a noteworthy enhancement in power and energy efficiency through the utilization of the CDM logic style as opposed to the C-CMOS structure. In addition, a comparative analysis of the circuit characteristics of the SEC encoder and decoder utilizing C-CMOS and CDM standard cells with varying technological specifications of 10nm, 14nm, 16nm, and 20nm is presented.To facilitate a rigorous evaluation of the cell libraries, Pedro's SEC and the conventional Hamming code are utilized for the purpose of efficient comparison and performance analysis. In general, this study showcases the capability of CDM in enhancing the energy efficiency of SEC codes at the transistor level.

The paper [43] makes an important contribution to the field of energy-efficient Single Error Correction (SEC) encoding and decoding. The CDM approach provides a promising solution for the optimization of SEC at the transistor level, thus allowing for higher efficiency and lower power consumption. The results show that CDM logic architecture yields an average improvement of 32.4% in power consumption and 30% in energy usage which has significant practical implications for the development of cost-effective and energy-efficient hardware for a range of applications, including IoT devices, memory storage, and security applications using SECs.

The research presented in [43] endeavors to demonstrate the advantages of incorporating the CDM logic style into Hamming and SEC codes for diverse applications such as IoT, memory, and secure data transmission devices. The VLSI industry is currently experiencing a growing demand for low power, low latency, and energy-efficient applications. The potential benefits of such applications in IoT particularly in the areas of cost reduction, power reduction, and energy efficiency is demonstrated. The simulations illustrate that utilizing CDM structures can offer solutions for more efficient energy consumption and power usage. The research findings indicate a reduction in power consumption by 32.4% and an increase in energy efficiency by 30.03%, while incurring a minimal speed trade-off of only 2.93%. Enhanced outcomes may be achieved by utilizing more advanced and efficient cells within the frequently employed cell libraries. The complex logic structure employed by CDM, coupled with an efficient transistor-level realization, enables the generation of multi-function outputs for enhanced circuit characteristics.

### C. EFFECT OF FEC ON ALOHA-BASED RANDOM ACCESS SYSTEMS

The rise of low-power, inexpensive terminals that intermittently send short data packets require changes to the protocol stack components, especially at the medium access control (MAC) layer. Traditional scheduling-based methods may not be effective and uncoordinated access regulations such as additive linkages online Hawaii area (ALOHA) may be preferable. The FEC can improve the performance but currently there is no analytical model that takes this into account. In [44], the authors derive precise formulas for the packet loss rate and spectral efficiency of ALOHA with FEC as well as time- and frequency-asynchronous ALOHA with FEC. They also analyze how different random-access control systems perform with and without FEC including scenarios such as an IoT system supported by LEO satellites. The results show that FEC makes ALOHA more competitive and advantageous for time- and frequency-asynchronous applications with time and frequency ALOHA may benefit more from FEC than traditional ALOHA. The authors also use Monte Carlo simulations to create a mathematical model which can precisely forecast the spectral efficiency and packet loss rate of different systems to find that the FEC can significantly improve SigFox-like systems targeting the return uplink of satellite communication systems. The study shows that the application of FEC in ALOHA can achieve equivalent outcomes in terms of packet loss rate and spectral efficiency, even in destructive collision channels. The authors also consider different channel-to-transmission bandwidth ratios and demonstrate that their model can correctly forecast packet loss rates and spectral efficiencies for actual systems [44].

### D. ECC IN WIRELESS SENSOR NETWORKS

The review in [45] provides an insightful overview of the various error control schemes used in wireless sensor networks. The authors have identified the opportunities and challenges associated with these schemes and presented them in a clear and concise manner. The paper goes on to highlight the opportunities that error control schemes present for wireless sensor networks including increased reliability, reduced energy consumption, and improved network performance. The authors also addressed the challenges associated with error control schemes such as increased complexity, higher energy consumption, and reduced network capacity. Throughout the paper, the authors provided numerous examples for the implementation of error control schemes in real-world wireless sensor networks, which further enhanced the value of the paper. They also provided a critical evaluation of each error control scheme, by highlighting its strengths and weaknesses and identifying areas for future research. The research review in [46] provides a systematic analysis of ECC used in WSNs. The authors have reviewed and analyzed the relevant literature on ECCs in WSNs and presented their findings in a explicit and concise manner. The paper begins with an introduction to provide a background on WSNs and the challenges they face in terms of error control. The basic concepts of ECCs and their applications in WSNs are explained. A detailed explanation of various ECC techniques, including Convolutional codes, Turbo codes, LDPC codes, and Polar codes is provided. The paper then goes on to highlight the key contributions of the reviewed literature including the performance evaluation of different ECCs in WSNs, the optimization of ECCs for WSNs, and the application of ECCs in specific WSN scenarios. The authors also identify the gaps and limitations in the current literature and suggest directions for future research. One of the strengths of the paper is its systematic approach to reviewing and analyzing the literature. The authors have clearly defined their search strategy, inclusion criteria, and data extraction process which enhances the validity and reliability of their findings. They have also used a comprehensive set of quality criteria to evaluate the selected studies which adds to the rigor of the review.

The evaluation of computational resources required for encoding and decoding operations is commonly referred to as complexity analysis in the context of ECC implementations. The process entails the evaluation of multiple factors including but not limited to the intricacy of encoding and decoding, the memory demands, the level of parallelism, the hardware intricacy, and the compromises linked to the implementation of ECC as shown in Figure 6. The term

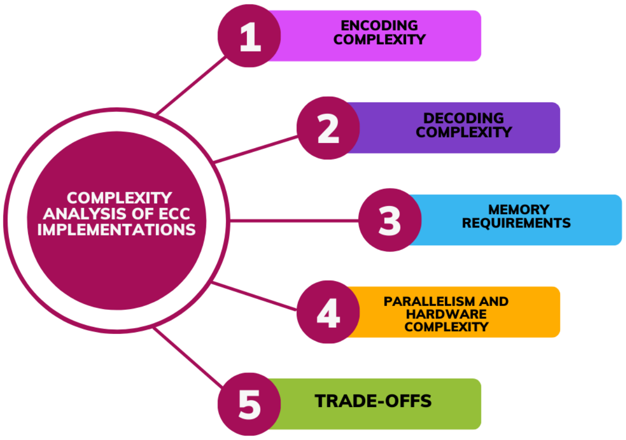

**FIGURE 6.** **Complexity analysis of error correction codes.**

''encoding complexity'' pertains to the level of computational resources required for the conversion of source data into a codeword through the utilization of ECC algorithms. The codeword generation process considers the quantity of operations, encompassing mathematical computations and transformations, which are necessary to produce the codeword. The concept of decoding complexity pertains to the computational resources necessary for retrieving the initial data from the codeword that has been received. The identification and correction of errors in received data necessitate the utilization of complex algorithms and processing procedures. The assessment of memory requirements pertains to the quantification of the memory or storage capacity necessary for the storage of ECC-related data structures and lookup tables throughout the encoding and decoding procedures. The investigation of parallelism and hardware complexity pertains to the evaluation of the capacity for parallel processing and the requisite hardware resources for the efficient implementation of ECC. The process of trade-offs entails the examination of the interconnections among different performance metrics including but not limited to error correction capability, computational complexity, memory usage, and hardware requirements. Comprehending the intricacies of the complexity analysis of elliptic curve cryptography (ECC) implementations can offer valuable insights into the computational requirements and resource trade-offs linked with diverse ECC schemes. This, in turn, can facilitate the process of selecting and optimizing ECC algorithms for specific applications.

The challenges posed by unreliable wireless links such as the broadcast nature of wireless transmissions, interference, noisy transmission channels, and frequent topology changes are significant. In order to address these obstacles, the authors in [56] introduce an innovative error identification and rectification mechanism known as LCPC codes, which exhibit abbreviated codeword lengths. The LCPC codes have been specifically engineered to exhibit reduced complexity and memory demands when contrasted with Turbo codes and LDPC codes. The study showcases outcomes which exhibit the superior efficacy of LCPC codes in comparison to Hamming codes, Reed-Solomon (RS) codes, and LDPC codes. The LCPC codes are capable of achieving a coding gain of up to 3 dB. The article emphasizes on the advantages of the suggested LCPC codes. The evaluation of the performance of LCPC codes is conducted by measuring the BER for Binary Phase Shift Keying (BPSK) modulation over AWGN and Rayleigh fading channels. A comparative analysis has been carried out utilizing Hamming codes, RS codes, BCH codes, as well as binary and non-binary LDPC codes. The outcomes in the paper demonstrate a noteworthy enhancement in BER efficacy in contrast to LDPC, RS, BCH, and Hamming coding techniques. The LCPC codes possess unique attributes which distinguish them from LDPC codes. These include simplified encoding and decoding procedures, minimal memory space demands (specifically, a mere 420 bits for LCPC (9, 4)), and the exclusion of iterations in the decoder process. The article outlines an innovative strategy for identifying and rectifying errors in advanced wireless networks by incorporating LCPC codes featuring abbreviated codeword lengths and the enhanced efficiency of LCPC codes in comparison to other established codes. LCPC codes present several benefits including reduced complexity, minimal memory demands, and enhanced bit error rate (BER) performance. As a result, LCPC codes hold significant potential as a viable option for wireless network implementations.

### *E. CHALLENGES OF ERROR CONTROL SCHEMES IN WIRELESS SENSOR NETWORKS*

In recent years, wireless sensor networks have become increasingly popular due to their potential for use in various applications including environmental monitoring, healthcare, and surveillance. However, these networks are often subject to interference and other sources of errors which can compromise their reliability and accuracy. In response to these challenges, researchers have developed various error control coding techniques to mitigate errors in wireless sensor networks. One of the research papers provides insights into error control coding in wireless sensor networks is authored by Pellenz et al. [47]. The authors provide a thorough examination of various error control coding methodologies and their implementation in wireless sensor networks. The manuscript presents a succinct and lucid exposition of error control coding, elucidates its underlying principles and its significance in the context of wireless sensor networks. Subsequently, the authors explain diverse categories of error control coding methodologies encompassing Block codes, Convolutional codes, and Turbo codes.The merits and demerits of individual code types and their potential applications in wireless sensor networks are elaborated. The pragmatic application of error control coding within wireless sensor networks is a noteworthy aspect of the paper. The comprehensive exposition is made on the integration of error control coding within the network architecture, while considering multiple factors such as energy efficiency, bandwidth utilization, and latency. Additionally, the paper deliberates on the difficulties linked with the execution of error control coding within wireless sensor networks due to limitations in resources. In its entirety, the paper constitutes a significant and noteworthy addition to the domain of error control coding pertaining to wireless sensor networks. The resource in question provides a thorough examination of various coding techniques including an analysis of their respective benefits and drawbacks, as well as their real-world application. As such, it is a valuable asset for professionals and scholars engaged in research and practice within this field. The manuscript exhibits a high degree of organization, lucidity, and impartiality in its exposition of the contemporary landscape of error control coding within wireless sensor networks. The authors in [26] provide a thorough analysis of ECC in the context of WSNs and present their findings in a clear and concise manner. The paper provides a background on the challenges of energy efficiency in WSNs and the role of ECC in addressing these challenges. The authors discuss different types of ECC techniques commonly used in WSNs such as FEC and automatic repeat request (ARQ), and explain the trade-offs between their energy efficiency and error correction capabilities. The evaluation of the energy efficiency of ECC in low-power WSNs based on a detailed study is presented. The energy consumption of different ECC techniques is compared under various network conditions to demonstrate the impact of different factors such as packet size, transmission rate, and signal-to-noise ratio on energy efficiency. The paper also discusses the limitations of ECC in low-power WSNs and identifies areas for future research. The authors highlight the need for more energy-efficient ECC techniques and suggest the integration of ECC with other energy-saving techniques such as adaptive modulation and coding and duty cycling.

The study conducted by [48] involves a thorough examination of the various strata comprising the WSN protocol stack namely the physical, data link, network, and transport layers. The investigation delves into the interplay between these layers with the aim of minimizing errors and enhancing the network's dependability and efficiency. The study conducted by the authors provides an overview of the latest techniques and algorithms employed for error control in WSNs. The review encompasses conventional error control mechanisms such as FEC and Automatic Repeat Request (ARQ), in addition to contemporary techniques such as network coding and cross-layer optimization. The manuscript additionally presents an exhaustive examination of the trade-offs among the aforementioned methodologies concerning their computational intricacy, energy utilization, and comprehensive efficacy in mitigating errors. The paper exhibits a notable attribute in its cross-layer methodology and acknowledges the intricate nature of error control as a predicament that necessitates synchronization and enhancement across various strata of the protocol stack. The article lists various instances of how cross-layer optimization can enhance error control in WSNs. These include modifying transmission power based on channel quality and utilizing network coding to enhance energy efficiency.

In [49], various error correcting schemes proposed for WSNs such as FEC, ARQ, and Hybrid ARQ (HARQ) are discussed along with a detailed analysis of the performance of these error correcting schemes using the NS-2 simulator focusing on packet loss rate and energy efficiency. The paper provides a valuable resource for researchers and practitioners working in the field of WSNs by highlighting the advantages and disadvantages of each scheme. The simulation results show that FEC provides the best performance in terms of packet loss rate while HARQ is the most energy-efficient scheme. This information can guide researchers and practitioners in selecting appropriate error correcting schemes based on the network requirements. In summary, the paper presents a thorough analysis of error correcting schemes for multi-hop WSNs and their performance evaluation. The discussion on the advantages and disadvantages of each scheme makes the paper a useful resource for anyone interested in designing and optimizing error correcting schemes for WSNs. In [50], Kolmogorov complexity is introduced for, any truly random linear code is considered ‘‘good’’ despite lack of a precise specification. Regardless of block length, randomly selecting a constructive pattern code generally fails the Gilbert-Varshamov constraint. Additionally, it compares linear and non-linear codes to show that non-linear codes are closer than linear codes on average. Shortened cyclic, generalized Reed-Solomon, and generic non-linear codes are evaluated under combined burst-and random-error correction decoding techniques. The decoding algorithms for general linear codes are covered. Full hard decision decoding and bounded soft decision decoding are discussed. Information set decoding is introduced and demonstrated to outperform previous methods notably exhaustive search algorithms for huge symbol fields. Performance and complexity trade-offs in decoding algorithms conclude the study. For the AWGN channel, bounded soft decision decoding performs twice as well as bounded hard decision decoding but with a higher complexity coefficient.The key heuristics of most combinatorial decoding techniques are combined in a new approach called continuous division. Also addressed is the possibility of decoding Convolutional codes with these techniques. It also sheds light on typical Linear codes weight structure and the absence of sets of k symbols with low rank [50]. The contributions and identified research gaps of ECC in wireless sensor networks is listed in Table 5.

Strong error correction codes known as LDPC codes are utilized in a variety of different communication and storage systems. On the other side, Hamming codes are error detection and repair codes for both are straightforward and very effective. The study in [51] proposes novel approaches to simplify the process of improving the error-correction capabilities of LDPC codes by capitalizing on

**TABLE 5.** Review of error correction codes for wireless sensor networks.

| Ref. No. | Contribution | Research Gaps Identified |
|---|---|---|
| [47] | Developing and implementing novel error control coding schemes specifically designed for wireless sensor networks, to improve the reliability and efficiency of communication in these networks. | The paper does not explore the impact of different network topologies on the performance of error control coding schemes in wireless sensor networks. This is an area where further research is needed to understand the impact of network topology on the reliability and efficiency of communication in wireless sensor networks. |
| [48] | Investigating the impact of different parameters on the performance of error control techniques in wireless sensor networks, such as transmission power, channel conditions, and network topology. | The paper focuses on the performance of error control techniques in terms of BER and does not consider other performance metrics such as packet delivery ratio , latency, and throughput. Further research can investigate the impact of error control techniques on these performance metrics in wireless sensor networks. |
| [49] | Evaluating the performance of different error correcting schemes in multi-hop wireless sensor networks under various scenarios, such as different network topologies, node densities, and traffic loads. | The paper does not investigate the impact of using different modulation schemes on the performance of error correcting schemes in multi-hop wireless sensor networks. |

the characteristics of Hamming codes while at the same time increasing their efficiency. It provides information on effective decoding algorithms, optimization strategies, and the trade-offs made between error correction performance and complexity.

The paper [52] examines LDPC codes based on Hamming codes and offers insights into ECC techniques. Using the properties of Hamming codes, the paper proposes low-complexity error correction techniques for LDPC codes. It examines effective decoding algorithms, optimization techniques, and error correction performance versus complexity trade-offs. This paper contributes to the comprehension of LDPC coding schemes by providing valuable insights into improving their error-correction capabilities.

In [53], authors describe an innovative multiple error correction scheme based on cross parity codes. The paper focuses specifically on temporal circuit defects caused by radiation interference. The proposed methodology uses cross parity codes to rectify multiple errors and reduces space overhead. Using finite field multipliers as example circuits, the efficacy of the methodology is demonstrated. The paper describes the capabilities of the proposed scheme to remedy multiple errors and achieve low area overhead in specific circuit implementations.

While [53] and [54] concentrate on error correction techniques but their specific application areas and methodologies differ. The first paper [53] explores error correction performance and efficient decoding algorithms for LDPC codes based on Hamming codes. In addition the paper presents a novel scheme for multiple error correction in circuits affected by radiation interference based on cross parity codes. In contrast, the second paper [54] addresses multiple error correction by introducing cross parity codes in circuits affected by radiation interference. Using specific circuit examples, the authors demonstrate the efficacy of their approach and discuss the area overhead implications.

In terms of its contributions, the first paper provides insights into low-complexity error correction techniques for LDPC codes which are extensively employed in a variety of communication and storage systems. It investigates the trade-offs between error correction performance and complexity, and offers practical implications for code design and optimization. The second paper presents a novel scheme for the remediation of multiple errors in circuits, with a focus on temporal errors caused by radiation interference. The authors propose a method employing cross parity codes and demonstrate its efficacy in reducing area overhead while achieving multiple error correction capability. When considered together [53] and [54] papers address various aspects of error correction in their respective contexts using distinct approaches and findings.

The authors in [56] highlight the significance of developing high-performance codes which possess low complexity encoding and decoding capabilities for upcoming wireless systems. These systems necessitate dependability in brief message situations and high throughput in extended message situations. The coding schemes comprise of Convolutional codes, Turbo codes, LDPC codes, and Polar codes were examined. The study analyzes the performance of the system in relation to BER across various information block lengths and code rates. The research encompasses a diverse range of scenarios involving high throughput and reliability. Furthermore, the study examines the convergence characteristics of Turbo and LDPC codes with respect to the number of iterations, as well as the influence of list size on Polar codes. The investigation of the impact of approximate decoding algorithms on the efficacy of said codes is undertaken. The comparison of BER among Convolutional, Turbo, LDPC, and Polar codes under different scenarios is provided. Except for Convolutional codes, the various codes demonstrate comparable performance with their proximity in performance becoming more pronounced as the length of the information block increases. The study enhances understanding of diverse channel coding techniques and their performance attributes in wireless communication systems. The resemblances and distinctions among Convolutional, Turbo, LDPC, and Polar codes provide significant perspectives into their efficacy under diverse communication circumstances. The results of this investigation may prove beneficial in the identification of suitable coding methodologies to cater for particular demands and limitations of wireless communication systems.

## IV. ANALYSIS OF RESULTS AND DISCUSSION

This section provides an in-depth analysis of the results and findings that are presented in this survey paper on advancements of error correction and detection techniques. The research primarily centers on various facets of error control coding within wireless communication systems encompassing Narrowband Internet of Things (NB-IoT) systems, hardware design that prioritizes energy efficiency, systems for controlling random access, and Wireless Sensor Networks (WSNs). The examination of error control coding in NB-IoT systems places significant emphasis on the implementation of adaptive coding and modulation (ACM). The proposed approach is based on the Association for Computing Machinery (ACM) framework which exhibits notable enhancements in energy efficiency and decreased error rates when compared to conventional fixed coding and modulation schemes. The significance of employing dynamic coding strategies capable of adjusting to fluctuating channel conditions enables the optimization of resource utilization and the improvement of overall system performance. This study highlights the practical benefits of utilizing this methodology to effectively meet the changing requirements of energy-efficient NB-IoT systems.

The examination of energy-efficient hardware design introduces the notion of Cell Design Methodology (CDM) and its influence on Single Error Correction (SEC) codes. The results reveal promising outcomes in minimizing power and energy consumption through the optimization of SEC codes using CDM. This technological progress has substantial ramifications for diverse applications specifically in the context of IoT devices, memory storage, and security systems that depend on energy-efficient hardware design. This study establishes a correlation between error control coding techniques and hardware efficiency thereby creating opportunities for the development of cost-effective and sustainable solutions. Moreover this study analyze the impact of FEC on the efficacy of ALOHA-based systems within the realm of random access control systems. The utilization of mathematical computations and Monte Carlo simulations has provided empirical evidence of the practical advantages offered by FEC especially in situations where there may be deviations in time and frequency synchronization. The results highlight the significant role of FEC in enhancing packet loss rates and spectral efficiency, specifically within the domain of satellite communication systems. This observation enhances the comprehension of the significance and efficacy of FEC in enhancing communication protocols and optimizing resource utilization. Expanding the breadth of the analysis, the exploration of error control mechanisms in Wireless Sensor Networks (WSNs) reveals an extensive evaluation of diverse error correction coding (ECC) approaches encompassing Convolutional, Turbo, LDPC, and Polar codes. The aforementioned methods are evaluated based on their advantages, disadvantages, and the difficulties encountered during their implementation in wireless sensor network (WSN) scenarios. This study emphasizes on the importance of error control mechanisms in enhancing the reliability, minimizing energy consumption, and optimizing network efficiency in wireless sensor networks (WSNs). In addition, this study offers a comprehensive analysis of ECC techniques, thereby providing researchers and practitioners with valuable insights to enhance the performance of wireless sensor networks for their real time applications.

Table 6 provides a comprehensive analysis of several error correcting methods utilized in the domain of LPWAN and IoT technologies offering valuable insights. The utilization of these strategies is of utmost importance in augmenting the dependability and precision of data transfer inside wireless communication systems. The use of each technique encompasses a wide array of disciplines such as environmental monitoring, asset tracking, industrial automation, and smart agriculture are amongst many others. The extensively studied codes in the field are: Hamming codes, Reed-Solomon codes, Turbo codes, LDPC codes, BCH codes, Convolutional codes, and Polar codes. Each of these codes offers unique and specific capabilities which include the capacity to identify and rectify errors, and provision of targeted data correction quantities.

When examining the practical application and incorporation of error control coding methods in real-life situations for the purpose of error correction in LPWANs, numerous suggestions and informative case studies come to light. In order to optimize error correction capabilities while preserving energy efficiency, it is crucial to implement adaptive coding schemes that can dynamically modify parameters according to the prevailing network conditions. Moreover, the integration of FEC and Automatic Repeat reQuest (ARQ) mechanisms in a hybrid fashion may present a beneficial trade-off between error correction capabilities and latency. The implementation of collaborative cross-layer optimization which encompasses the physical and medium access control (MAC) layers holds the potential to develop customized strategies that are in line with the characteristics of LPWANs. It is recommended to focus on the development of energy-efficient hardware implementations of error control coding algorithms to tackle the issue of energy consumption. The incorporation of real-world channel modeling which considers various factors such as fading and interference, is crucial in guiding the development of coding techniques. The case studies considered in this paper provide valuable insights into these recommendations. For instance, one such case study involves the examination of LDPC codes in the LoRaWAN protocol. Additionally, second case study involves the evaluation of adaptive coding in NB-IoT networks. Furthermore, a third case study focuses on investigating hybrid coding within Sigfox's LPWAN technology. The practical significance of these strategies can be emphasized through the collaboration with the Weightless-P standard and advancement of energy-efficient hardware-accelerated LDPC decoders for LPWAN devices. In view of the Table 6, it is significantly important to acknowledge that technology and research in error correction for LPWAN and IoT technologies are always advancing. Therefore, it is imperative to regularly update and reference the most recent literature to obtain the most accurate and up-to-date insights.

**TABLE 6.** Analysis of error correction techniques in LPWAN and IoT technologies.

| Ref. No | Error Technique | LPWAN/IoT Technology | Applications | Capabilities | Data Detection | Data Correction | Maximum Correctable Data |
|---|---|---|---|---|---|---|---|
| [18] | Hamming Code | LoRaWAN, NB-IoT | Environmental Monitoring | Detects and corrects multiple errors | Yes | Yes | Varies |
| [25] | Reed-Solomon Code | LoRaWAN, Sigfox | Asset Tracking | Corrects burst errors, but suffers, data loss | Yes | Yes | Varies |
| [23] | Turbo Codes | LoRaWAN, NB-IoT | Industrial Automation | Iterative decoding and error correction | Yes | Yes | Moderate |
| [32] [52] | LDPC Codes | NB-IoT | Smart Agriculture | Low error rates and efficient correction | Yes | Yes | High |
| [36] [41] | BCH Codes | LoRaWAN, Sigfox | Smart Cities | Detects and corrects multiple errors | Yes | Yes | Varies |
| [23] | Convolutional Code | LoRaWAN, NB-IoT | Healthcare Monitoring | Continuous error correction | Yes | No | Limited |
| [23] [42] | Polar Codes | LoRaWAN, NB-IoT | Wearable Devices | High reliability with short packets | Yes | Yes | Moderate |
| [36] | FEC | Various LPWAN/IoT | Various | Varies | Yes | Yes | Varies |
| [21] [22] | Trellis Coding | LoRaWAN, NB-IoT | Wireless Sensing | Sequential decoding and error correction | Yes | Yes | Varies |

**TABLE 7.** Comparative trade-offs of error correction coding techniques.

| Error Technique | Tradeoffs Identified during Literature Review |
|---|---|
| Hamming Code | Limited error correction capability. Inefficient for large data blocks. More suitable for low error rates, and shorter data lengths. |
| Reed-Solomon Code | Overhead increases as error correction capability grows. Complexity of encoding and decoding algorithms. Effective for burst errors. Inefficient for random errors. |
| Turbo Codes | Higher complexity due to iterative decoding. Tradeoff exists between performance and decoding complexity. Tailored for higher SNRs. |
| LDPC Codes | Complexity increases with larger block sizes. Requires parameter tuning for optimal performance, and performs well at high SNRs. |
| BCH Codes | Correction capability increases with the code length. Complexity increases with code length. Effective for burst and random errors but does not provide the highest performance in all scenarios. |
| Convolutional Code | Continuous error correction at the cost of redundancy, complex decoding algorithms, and performs good with consistent error patterns. |
| Polar Codes | Lower encoding complexity. Requires careful design, and excellent performance for specific applications but not universally optimal. |
| FEC (Forward Error Correction) | Higher redundancy for stronger error correction. Increased decoding complexity, and effectiveness depends on coding scheme and modulation choice. |
| Trellis Coding | Moderate complexity. Performance depends on trellis structure and modulation. Struggles to achieve good performance with more advanced codes. |

Table 7 provides a succinct summary of the inherent trade-offs associated with different error correcting coding schemes. Every scheme has unique advantages and disadvantages which affect their appropriateness for various communication settings. Hamming codes provide a restricted level of error correction capability but they demonstrate efficiency when applied to shorter data lengths. On the other hand, Reed-Solomon codes exhibit superior performance in correcting burst errors, however they may experience a higher degree of overhead.

Turbo codes are characterized by their iterative decoding complexity which results in enhanced performance at greater signal-to-noise ratios (SNRs) whereas LDPC codes demonstrate resilience at high SNRs albeit necessitating meticulous parameter tweaking. BCH codes exhibit a trade-off between error correction capabilities and complexity, Convolutional codes prioritize continuous error correction at the cost of redundancy while Polar codes strike a balance between complexity and performance optimization. The concept of FEC involves the use of increased redundancy to provide more robust error correction whereas Trellis Coding presents a modest level of complexity with its performance being contingent upon the specific trellis structure and selection of adequate modulation. These insights provide valuable guidance in making educated decisions when choosing the most appropriate error correction strategy for specific communication systems.

## V. CONCLUSION

This review paper provides an analysis of error control coding in diverse domains such as Narrowband IoT (NB-IoT) systems, energy-efficient hardware design, random access systems, and WSNs. The paper draws conclusions based on the examination of these various aspects. Each manuscript provides significant perspectives, presents novel remedies, assesses efficacy, and underscores pragmatic ramifications for their corresponding error correction and detection disciplines.

The initial collection of documents centers on the topic of error control coding within NB-IoT systems. The channel coding scheme which has been proposed is founded on ACM. This scheme exhibits superior energy efficiency and reduced error rates when compared to conventional fixed coding and modulation schemes. The presented study aims to cater for the increasing need of energy-efficient channel coding techniques in NB-IoT systems, highlighting the advantages of the suggested methodology.

The subsequent collection of documents explores the enhancement of SEC codes with the aim of achieving energy efficiency in hardware design. The Cell Design Methodology (CDM) approach has demonstrated encouraging outcomes in the context of minimizing power and energy consumption. This underscores the possibility of developing hardware being both energy-efficient and cost-effective for a wide range of applications. The findings hold great importance for various applications such as IoT devices, memory storage, and security applications which heavily rely on Secure Element Chips (SECs).

An additional article analyzed in this paper, investigates the effects of FEC on ALOHA-based random access systems. The findings of the research indicate that the utilization of FEC amplifies the competitiveness and benefits of ALOHA in applications which involve asynchronous time and frequency. The study makes a significant contribution towards enhancing the packet loss rate and spectral efficiency in ALOHA-based systems with a specific focus on IoT and satellite communication systems. This is achieved through the provision of precise formulas, analytical models, and simulations whilst encompassing the topic of error control schemes within the context of WSNs. The study presented in [45] provides a thorough examination of diverse error control methodologies, such as Convolutional codes, Turbo codes, LDPC codes, and Polar codes. The article elucidates the prospects and obstacles linked with error control mechanisms in WSNs including heightened dependability, diminished energy consumption, and enhanced network efficacy. Additionally, it serves to pinpoint areas of deficiency and proposes avenues for prospective investigation. Finally, the review encompasses scholarly articles that examine the difficulties and pragmatic application of error control coding in wireless sensor networks. The papers offered a comprehensive understanding of error control coding methodologies for WSNs, and their amalgamation into network frameworks. The interplay between energy efficiency and error correction capabilities to tackle the obstacles that arise in resource-limited wireless sensor networks is elucidated. The results of the study provide significant insights and information for scholars and professionals engaged in the relevant areas of research and practice in error correcting techniques.

Conclusively, this analytical review paper presents a comprehensive overview of the latest research on error control coding in diverse domains of wireless communication with a particular focus on LPWAN and IoT technologies. It aims to provide a thorough understanding of the challenges, opportunities, and practical implications associated with these technologies. The rigorous research presented offers valuable contributions to the development of error control coding techniques which in turn facilitate enhancements in energy efficiency, reliability, and performance in various systems such as NB-IoT, hardware design, random access systems, and WSNs. This review paper not only showcases the advancements achieved thus far but also pinpoints the research loopholes for future research and enhancement in the area of error control coding pertaining to forthcoming wireless communication systems.

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