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A Combined Statistical and Prioritized Unequal Error Protection Approach for LDPC Codes

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Abstract

The combination of powerful error-correcting codes like Low Density Parity Check (LDPC) codes and Quadrature Amplitude Modulation (QAM) has been widely adopted in wireless communication standards such as IEEE 802.11n and DVB-T2. Recently, various Unequal Error Protection (UEP) schemes have been proposed that leverage the non-uniform degree distribution of bit nodes in irregular LDPC codes. Similarly, schemes that utilize the inherent UEP properties of the QAM constellation have also been developed. This paper proposes a hybrid UEP scheme for LDPC codes with QAM. The scheme maps systematic bits of the LDPC encoded symbols to the QAM constellation based on the statistical distribution of source symbols. Specifically, symbols with the highest probabilities of occurrence are assigned to the low-power region of the QAM constellation, while those with lower probabilities are mapped to the high-power region. This reduction in overall transmission power enables increased spacing between QAM constellation points. Additionally, the scheme maps parity bits with the highest degree, based on the LDPC code-word's bit node degree distribution, to prioritized QAM constellation points. Simulations using IEEE 802.11n LDPC codes show that the proposed scheme achieves up to a 0.91 dB improvement in Eb/No compared to other UEP schemes across a range of Bit Error Rate (BER) values.

Keywords: Low-Density Parity-Check codes, Quadrature Amplitude Modulation, Unequal Error Protection.

1. Introduction

In 1962, Low-Density Parity-Check (LDPC) codes, a class of linear block codes, were invented by Gallagher [1]. LDPC codes were re-introduced in 1996 by David Mackay [2], who later, in 1998, developed Non-Binary LDPC codes that surpassed traditional LDPC codes in performance [3]. Since LDPC codes approach the Shannon limit, they are considered some of the most powerful error-correcting codes available. Consequently, several communication standards such as WiMax [5], DVB-T2 [6], and IEEE 802.11n [7] have incorporated LDPC codes. The 802.11n standard, for example, combines QAM with LDPC codes and supports a range of code lengths from 648 to 1944 with code rates of 1/2, 2/3, 3/4, and 5/6 [7], [8].

In recent years, numerous studies have demonstrated that Unequal Error Protection (UEP) can provide significant performance improvements when applied to LDPC codes and other coding schemes combined with QAM. An overview of UEP schemes for LDPC codes, as well as those exploiting the UEP potential of QAM, is presented below.

QAM constellations have a unique property that makes them suitable for UEP, as demonstrated by a bit-reordering technique in [9]. The authors in [9] combined LTE Turbo codes with QAM, utilizing UEP to give stronger protection to the systematic bits, resulting in significant performance improvements. In [10], this work was extended with joint source-channel decoding for LTE Turbo codes. Similarly, the principle of UEP was applied to IEEE 802.11n LDPC codes along with a modified hybrid ARQ scheme in [11]. In [12], a novel scheme mapped more important bits of an image to variable nodes with higher degrees in irregular LDPC codes. The systematic bits were mapped to power-efficient QAM constellation points, while the parity check bits were mapped to the spectrally efficient 16-QAM constellation. This scheme achieved substantial performance gains. Additionally, [13] employed an UEP strategy based on bit reliability in a non-binary LDPC coded modulation system, achieving gains between 0.1 and 0.5 dB at a Bit Error Rate (BER) of 10^-5. Further work in [14] developed structured rate-compatible codes with UEP, optimizing codes for both source-relay and source-destination systems. Significant performance gains were obtained over conventional and punctured LDPC codes. Finally, a statistical QAM-based modulation scheme for low-complexity video transmission was proposed in [15], where the most frequent pixel values were mapped to low-energy QAM points, reducing the energy needed for transmission and improving BER performance.

In this paper, a hybrid UEP scheme for binary LDPC codes combined with QAM is introduced. The scheme assumes the source is a set of variable-length coded characters with an unequal probability distribution. It utilizes the statistical distribution of the source symbols to map the systematic bits of the LDPC encoded symbols to the QAM constellation. Specifically, symbols with the highest probabilities are mapped to the low-power region of the QAM constellation, while symbols with lower probabilities are mapped to the high-power region. This reduces the overall transmission power and increases the spacing between constellation points for the same average energy. Additionally, the scheme maps parity bits with the highest degree, based on the LDPC code's bit node degree distribution, to prioritized QAM constellation points. The proposed hybrid UEP scheme integrates statistical QAM (S-QAM), prioritized constellation mapping, and the uneven degree distribution of bit nodes with binary LDPC codes. Simulations using IEEE 802.11n LDPC codes demonstrated that the proposed scheme offers gains ranging from 0.23 dB to 0.91 dB in Eb/No for code rates of 1/2, 2/3, and 3/4, compared to other UEP schemes across a range of BER values. This work introduces a new UEP scheme that hybridizes performance-enhancing techniques such as UEP and S-QAM.

The remainder of this paper is structured as follows: Section 2 describes the transmitter and receiver system models using the hybrid UEP scheme. Section 3 presents simulation results and analysis. Section 4 concludes the paper.

2. TRANSMITTER AND RECEIVER SYSTEMS FOR HYBRID SCHEME

2.1 TRANSMITTER

The input data consists of a random alphabet source with an equiprobable probability distribution. The alphabet symbols and their corresponding probabilities are given in

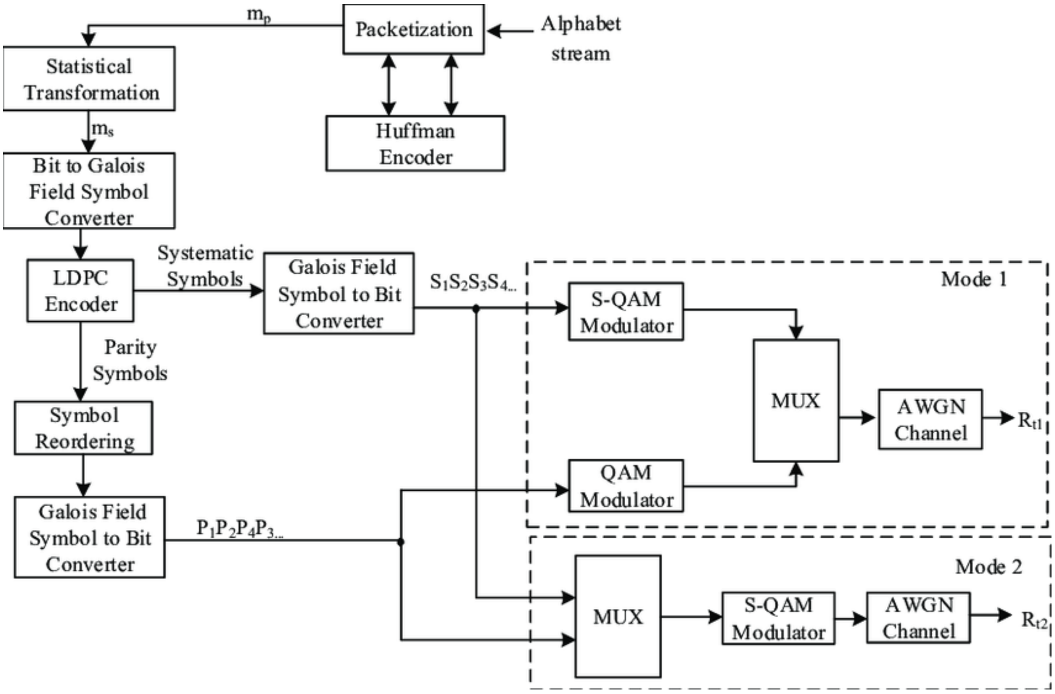

Fig. 1. Transmitter with statistical QAM transformation and bit reordering

The figure depicts a transmitter system for a communication scheme that combines Low-Density Parity-Check (LDPC) codes with Quadrature Amplitude Modulation (QAM), incorporating Unequal Error Protection (UEP) and Statistical QAM (S-QAM).

The figure illustrates a communication system that combines Low-Density Parity-Check (LDPC) codes with Quadrature Amplitude Modulation (QAM) to implement an Unequal Error Protection (UEP) scheme. The system begins with an alphabet stream that undergoes a **statistical transformation** to prepare the data for encoding. The transformed data is then processed by a **Huffman encoder**, which reduces the data size by applying entropy coding. After this, a **bit to Galois field symbol converter** is used to map the bits into Galois field symbols for further processing.

The LDPC encoder takes the Galois field symbols and generates **systematic symbols** and **parity symbols**, which are critical for error correction. These symbols are reordered to optimize their arrangement before being converted back into bits by another **Galois field symbol to bit converter**. Following this, the systematic symbols are mapped onto a QAM constellation. Some symbols are mapped to **S-QAM (Statistical QAM) points**, based on their probability of occurrence, to provide better protection to more frequent symbols. The rest of the systematic symbols are mapped to regular QAM points.

The outputs from both the **S-QAM modulator** and the **QAM modulator** are multiplexed together using a **MUX**, which combines them into a single transmission stream. This combined signal is then transmitted over an **AWGN (Additive White Gaussian Noise) channel**, simulating real-world conditions where noise affects the signal. The system can operate in two different transmission modes (**Mode 1** and **Mode 2**), each with its own data rate (**R1** and **R2**), allowing flexibility in how the data is transmitted depending on the channel conditions.

2.2 RECEIVER

For the Hybrid 1 scheme, the received QAM symbols, denoted as **R_t**, are first **de-multiplexed** into separate systematic and parity symbols. The **systematic symbols** are then demodulated using the **S-QAM demodulator**, while the **parity symbols** are demodulated using the conventional 16-QAM demodulator, as shown in the figure. This separation allows for the different error protection levels applied to the systematic and parity bits during transmission to be properly processed.

For the Hybrid 2 scheme, the received signal **R_t** is first demodulated using the **S-QAM demodulator** to obtain **soft bits**. These soft bits are then de-multiplexed into the systematic and parity components, allowing the receiver to process the data with appropriate error correction methods for each part of the signal.

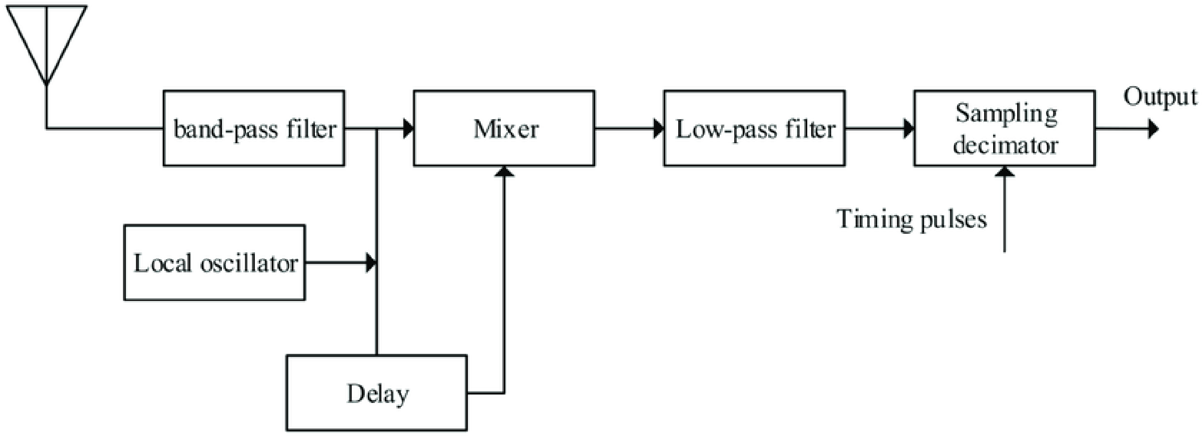

Fig. 2. Block diagram of the receiver system.

In the **receiver system**, as shown in **Fig. 2**, the process starts with the received QAM symbols, denoted as **R_t**, which represent the transmitted signal that has been received over the communication channel. These received symbols are affected by noise and other channel impairments, so the first step is to **de-multiplex** them into two distinct parts: **systematic symbols** and **parity symbols**. This separation is essential because the systematic and parity symbols are treated differently due to the Unequal Error Protection (UEP) scheme applied during transmission.

For the **Hybrid 1 scheme**, once the QAM symbols are de-multiplexed, the **systematic symbols** are demodulated using an **S-QAM demodulator**. The S-QAM demodulator is specifically designed to take into account the unequal error protection applied to the systematic symbols, meaning that the more important, or more frequent, systematic bits are given higher priority for error correction. This demodulation process effectively recovers the data corresponding to the systematic bits by estimating the transmitted symbols while leveraging the additional protection provided to them during transmission.

Meanwhile, the **parity symbols**, which are less critical compared to the systematic bits, are demodulated using a **standard 16-QAM demodulator**. This simpler demodulation is suitable because the parity bits have a lower priority in terms of protection, and their purpose is primarily to assist in error correction rather than carry essential data. Therefore, a conventional 16-QAM demodulator, typically used for standard QAM signals, is adequate for recovering the parity bits.

For the **Hybrid 2 scheme**, the process starts similarly with the reception of the **R_t** symbols. However, before de-multiplexing, the received symbols are first demodulated using the **S-QAM demodulator** to generate **soft bits**. Soft bits are a more detailed representation of the received symbols, as they provide not only the estimated values of the bits but also their confidence levels, which is crucial for more accurate decoding. After obtaining these soft bits, they are **de-multiplexed** into **systematic** and **parity** parts, allowing the receiver to separate the more critical systematic data from the less important parity information. This approach allows the receiver to make more informed decisions when processing the data, taking advantage of the soft information in the subsequent decoding steps.

In summary, the receiver system described in **Fig. 6** is designed to handle different types of symbols (systematic and parity) with varying degrees of protection. It employs different demodulation techniques, such as S-QAM for systematic symbols and conventional 16-QAM for parity symbols, depending on their importance in the error protection scheme. Additionally, the Hybrid 2 scheme incorporates the use of soft bit demodulation, providing more detailed information to improve the accuracy of the decoding process.

3. SIMULATION RESULTS AND ANALYSIS

3.1. SIMULATION RESULTS WITH 16-QAM

The performance of six different schemes using **binary LDPC codes** with **16-QAM** and **64-QAM** modulation schemes is compared. The schemes evaluated are:

- **Scheme 1**: Hybrid 1 scheme.
- **Scheme 2**: Hybrid 2 scheme.
- **Scheme 3**: Hybrid 1 scheme with statistical QAM mapping, but without UEP.
- **Scheme 4**: Hybrid 2 scheme with statistical QAM mapping, but without UEP.
- **Scheme 5**: UEP with bit reordering for both systematic and parity bits and conventional QAM.
- **Scheme 6**: Conventional LDPC encoding and decoding without UEP.

The simulations were conducted using **MATLAB®** with the following parameters:

- **Number of decoding iterations**: T = 20.
- **Channel Model**: Complex AWGN (Additive White Gaussian Noise).
- **Modulation**: 16-QAM and 64-QAM.
- **Code-rates**: 1/2, 2/3, and 3/4.
- **Code-length**: G = 648.
- **Total number of transmitted alphabets**: 476,191 (approximately 1 million bits).

3.1 Simulation Results with 16-QAM

Figures 7-9 present the **Bit Error Rate (BER)** versus **Eb/No** for the six schemes using **16-QAM** modulation and the different code rates (1/2, 2/3, and 3/4).

- **Observations**:
    - **Hybrid 1** and **Hybrid 2** schemes (Schemes 1 and 2) consistently provide the highest **Eb/No** gains compared to **Scheme 6** (conventional LDPC with no UEP) across all tested code rates, particularly for BER values less than 10^{-2}.
    - **Scheme 1 (Hybrid 1)** provides **Eb/No** gains of:
        - **0.23 dB** for **1/2** code-rate.
        - **0.34 dB** for **2/3** code-rate.
        - **0.68 dB** for **3/4** code-rate, in the range **$10^{-3} \leq$ BER $\leq 10^{-5}$**.
    - **Scheme 2 (Hybrid 2)** provides gains of:
        - **0.3 dB** for **1/2** code-rate.
        - **0.68 dB** for **2/3** code-rate.
        - **0.62 dB** for **3/4** code-rate, in the same **BER** range.
    - Thus, **Scheme 2 (Hybrid 2)** outperforms **Scheme 1 (Hybrid 1)** by:
        - **0.1 dB** for **1/2** code-rate.
        - **0.3 dB** for **2/3** code-rate.
        - **0.06 dB** for **3/4** code-rate.
    - **In the region BER $\geq 10^{-2}$**, the hybrid schemes (Schemes 1 and 2) show no significant gain over **Schemes 5 and 6**.
- **Scheme 5** (UEP with bit reordering and conventional QAM) provides **Eb/No** gains mainly at higher **BER** values (greater than 10^{-2}), with the maximum gain being:
    - **2 dB** for **LDPC code-rate 1/2**.
    - The minimum gain being **0.4 dB** for **LDPC code-rate 3/4**.
    - However, at **BER** values lower than 10^{-3}, **Scheme 5** provides:
        - **0.17 dB** gain for **LDPC code-rate 3/4**.
        - Almost no gain for **LDPC code-rate 1/2**.

  - The variation in gains in **Scheme 5** at different code-rates is due to the differences in the degree variations of bit nodes in the LDPC parity check matrix used for **code-rate 3/4** compared to **code-rate 1/2**.
- **Comparison of Hybrid Schemes**: The **Eb/No** gain provided by **Hybrid 1 (Scheme 1)** compared to **Scheme 3** (Hybrid 1 with statistical QAM but without UEP) and the gain of **Hybrid 2 (Scheme 2)** compared to **Scheme 4** (Hybrid 2 with statistical QAM but without UEP) is influenced by the variation in **parity bit node degrees**.
  - In most cases, **Scheme 1** provides an **additional 0.1 dB** gain compared to **Scheme 3**.
  - Similarly, **Scheme 2** provides a **0.1 dB** gain compared to **Scheme 4**.

In summary, the hybrid schemes (**Scheme 1 and Scheme 2**) demonstrate better performance compared to the conventional LDPC schemes (**Scheme 6**) in terms of **Eb/No** gains for lower **BER** values, especially when UEP and statistical QAM mapping are applied. Additionally, **Scheme 5** provides benefits for higher **BER** values, and the performance of the hybrid schemes improves with the variation in parity bit node degrees.

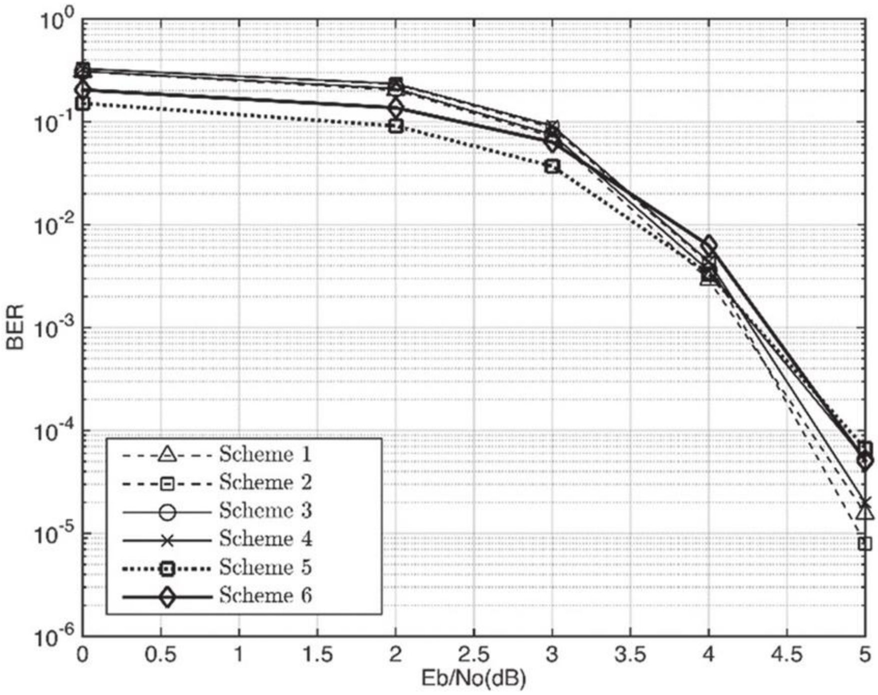

Fig. 3. Graph of Eb/No against BER using 16-QAM with R=1/2.

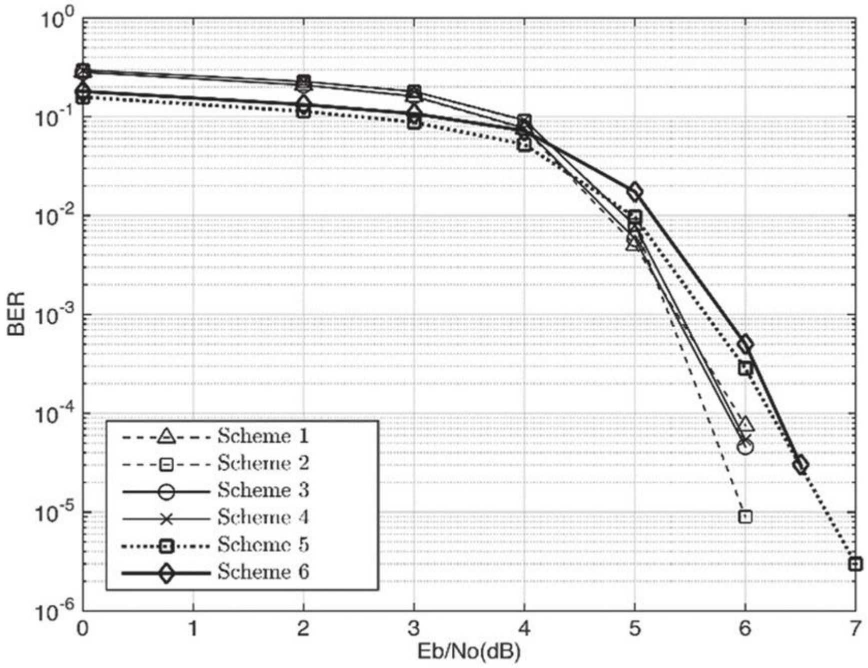

Fig. 4. Graph of Eb/No against BER using 16-QAM with R=2/3.

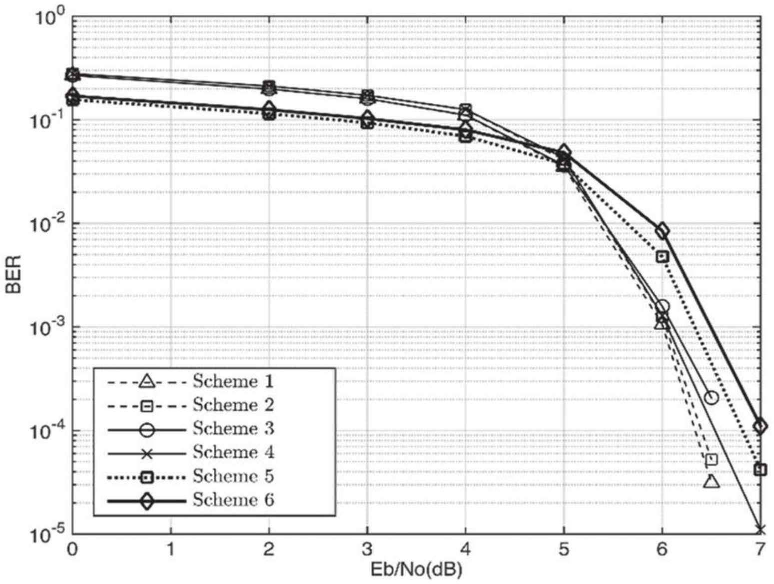

Fig. 5. Graph of Eb/No against BER using 16-QAM with R=3/4.

Analysis of Hybrid Scheme Performance with 64-QAM vs. 16-QAM

When comparing the performance of the proposed hybrid schemes using 64-QAM and 16-QAM, the results indicate that 64-QAM offers higher Eb/No gains. This can be attributed to the larger separation distances between the constellation points in 64-QAM compared to 16-QAM. Larger separation distances improve the signal-to-noise ratio (SNR), making the signal easier to distinguish and thus leading to a lower Bit Error Rate (BER). The specific values for these separation distances are presented in Tables 3 and 4.

Hybrid Scheme Performance:

With 16-QAM, Hybrid 2 outperforms Hybrid 1, providing better Eb/No gains.

With 64-QAM, the situation reverses, and Hybrid 1 outperforms Hybrid 2. This suggests that the Hybrid 1 scheme is more efficient when the higher constellation density of 64-QAM is utilized.

Code-rate Analysis:

The proposed schemes perform better with code-rates 3/4 and 2/3 compared to code-rate 1/2. This is because, at higher code-rates, the bit nodes corresponding to parity bits exhibit greater degree variations. The variations in degree help in better error-correction capabilities, thus improving the overall performance.

Hybrid schemes can also improve their performance with code-rate 1/2 by selecting an LDPC parity check matrix with higher degree variations for the parity bits.

Performance Beyond BER $\geq 10^{-2}$:

It is evident that in the high BER range (BER $\geq 10^{-2}$), the proposed Hybrid 1 and Hybrid 2 schemes are outperformed by Scheme 5 (UEP with bit reordering) and Scheme 6 (conventional LDPC). However, these hybrid schemes outperform Scheme 5 and Scheme 6 in the useful BER range (BER $\leq 10^{-2}$), where most communication systems operate.

4. CONCLUSION

In this paper, two versions of a hybrid Unequal Error Protection (UEP) scheme for **IEEE 802.11n LDPC codes** with **16-QAM** and **64-QAM** modulations were proposed. The key idea behind the hybrid scheme is to map QAM symbols with higher probability occurrences to the low-power regions of the QAM constellation. This reduces the overall transmission power, which in turn allows for greater separation between the constellation points, leading to a lower **Bit Error Rate (BER)**. Additionally, the scheme incorporates a **bit reordering** technique prior to modulation, providing better protection for the higher-priority parity bits.

The simulation results showed that the proposed schemes provided a maximum **Eb/No** gain of **0.68 dB** for **16-QAM** and **0.91 dB** for **64-QAM**, for **BER** values lower than 10^{-2}. The **64-QAM** modulation, with its larger separation between constellation points, outperformed **16-QAM**, showing the advantages of using higher-order modulations in terms of improved **SNR** and reduced **BER**. Moreover, the hybrid schemes performed better at higher code-rates (such as 3/4 and 2/3) because of the greater degree variations in the parity bit nodes. However, the hybrid schemes were outperformed by **Scheme 5** (UEP with bit reordering) and **Scheme 6** (conventional LDPC) in the **high BER range (BER $\geq 10^{-2}$)**, but showed significant improvement in the more practical range (BER $\leq 10^{-2}$). For future work, the authors suggest refining the parameter tuning for the hybrid schemes to improve performance in the **high BER region**. Additionally, the integration of other **UEP schemes** and the implementation of **Non-Binary LDPC codes** with advanced **decoding algorithms** like the **Belief-Propagation Algorithm** could further enhance the performance of the proposed hybrid scheme. Overall, the new hybrid UEP scheme demonstrates potential gains of up to **0.91 dB** in **Eb/No** compared to existing UEP schemes, with room for further optimization in future research. Parameter Tuning: The hybrid schemes showed challenges in tuning parameters to improve performance for BER > 10^{-2}. Future work will focus on refining these parameters to improve the high BER region. Integration of Other UEP Schemes: Exploring the integration of other UEP schemes to achieve additional gains. Non-Binary LDPC Codes: Implementing the hybrid UEP scheme with Non-Binary LDPC codes and advanced decoding algorithms, such as the Belief-Propagation Algorithm, could further enhance performance. In summary, the proposed hybrid UEP scheme demonstrates the potential to achieve up to 0.91 dB Eb/No gain over existing UEP schemes, with the possibility of further optimization for higher BER values in future research.

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