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Simulation of a Data Transmission System Based on Hamming (7,4) Coding

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Abstract
Noise and channel impairments can significantly degrade the reliability and integrity of modern data transmission systems, especially in practical network environments where interference, attenuation, and random disturbances are unavoidable. This paper presents the design and simulation of a data transmission system between two computers over a TCP/IP network, in which the Hamming (7,4) code is employed for single-bit error detection and correction. The system is implemented using a client–server architecture on a LAN/Wi-Fi platform, where data are encoded at the sender, transmitted via TCP sockets, and decoded at the receiver. To emulate transmission errors, a Binary Symmetric Channel (BSC) noise model with adjustable bit error probability is incorporated into the communication process. Experimental results under various noise levels show that the Hamming (7,4) code significantly reduces the bit error rate, effectively corrects single-bit errors, and successfully reconstructs the original data sequence under moderate noise conditions. The proposed model not only validates theoretical principles of linear block codes but also provides an intuitive, hands-on, and extensible platform for teaching and laboratory practice in digital communications, computer networks, and error-control coding.

Keywords: TCP/IP, Hamming (7,4), Error Correction, Data Transmission

1. Introduction

In modern data transmission systems, information reliability is a fundamental requirement, particularly in wireless networks, Internet of Things (IoT) infrastructures, industrial automation systems, and military–aerospace communications, where transmission channels are frequently exposed to thermal noise, electromagnetic interference, fading, congestion, variable latency, and unstable link quality [1, 2, 7]. As data rates continue to increase and networked devices become more densely deployed, even small error probabilities can significantly affect system performance and application-level quality of service. Ensuring accurate and timely delivery of information is therefore a central objective in the design of contemporary communication systems.

Although the TCP/IP protocol stack integrates several reliability mechanisms—such as checksums for error detection, acknowledgments, packet retransmission, sliding-window flow control, and congestion control—these mechanisms are primarily based on Automatic Repeat reQuest (ARQ). In ARQ-based schemes, corrupted packets are discarded and retransmitted after detection. While effective in relatively clean channels, this approach may lead to substantial performance degradation in high-error or high-latency environments. Frequent retransmissions increase end-to-end delay, reduce effective throughput, and consume additional network resources, which is particularly undesirable for real-time and delay-sensitive applications such as video streaming, remote control, industrial monitoring, and mission-critical systems [10, 13].

To mitigate these limitations, numerous studies have investigated the integration of Forward Error Correction (FEC) techniques at the physical or application layer to enhance reliability without relying solely on retransmission. By adding structured redundancy to the transmitted data, FEC enables the receiver to detect and correct certain errors locally, thereby reducing retransmission frequency and improving overall efficiency. Zhang *et al.* [10] demonstrated that combining FEC with TCP/IP over noisy channels can significantly reduce retransmissions and increase throughput. Similarly, Unal and Stojanovic [13] emphasized the importance of FEC in high-rate communication systems operating under severe noise conditions, where retransmission-based approaches become inefficient or impractical. Among linear block codes, Hamming codes occupy a prominent position due to their elegant mathematical structure, capability to detect and correct single-bit errors, and low computational complexity. These properties make them highly suitable for both hardware and software implementation. Recent research confirms their continued relevance in diverse applications, including digital memory protection, embedded systems, wireless sensor networks, and high-speed data transmission systems [3, 5, 6, 9, 11]. Freitas *et al.* [3] analyzed the effectiveness of Hamming coding in 32-bit memory architectures, while Tran *et al.* [5] and Kumar and Singh [6] demonstrated practical implementations for error control in digital systems. Furthermore, Park and Kim [9] proposed optimized decoding architectures to support high-speed and resource-efficient designs.

In communication scenarios characterized by burst errors or extremely low target error rates, more powerful coding schemes—such as BCH, Reed–Solomon, or LDPC codes—are typically preferred due to their stronger correction capabilities [7, 12]. However, these codes often require more complex encoding and decoding algorithms, increased computational resources, and sophisticated hardware support. Such complexity may pose challenges for introductory laboratory environments and foundational training courses. In contrast, the Hamming (7,4) code, with its intuitive parity-check structure, straightforward matrix representation, and moderate code rate of 57.1% (four data bits and three parity bits), remains an excellent pedagogical tool. It allows learners to clearly observe bit-level error detection and correction processes while maintaining manageable implementation complexity.

Based on these considerations, this paper does not aim to introduce a novel error-correcting algorithm. Instead, it develops a comprehensive simulation model of data transmission between two computers over a TCP/IP network, incorporating the Hamming (7,4) code for single-bit error detection and correction. The primary contributions of this study are as follows:

1. development of a visual and practical simulation framework for TCP/IP data transmission under noisy conditions;
2. detailed illustration of Hamming (7,4) encoding and decoding mechanisms within a client–server architecture;
3. quantitative evaluation of data recovery performance and analysis of the impact of bit errors on system reliability;
4. provision of an extensible experimental platform suitable for education, laboratory practice, and further research in digital communications and computer networks.

2. System Model and Methodology

The objective of this study is not to reproduce the complex physical characteristics of real communication channels, but rather to develop a visual and easy-to-implement simulation model for educational purposes in data transmission, TCP/IP networking, and error-correcting codes. The proposed model enables observation of the impact of bit errors and the effectiveness of the Hamming (7,4) mechanism in a simulated data transmission environment between two computers.

2.1. TCP/IP Transmission Model

2.1.1. Client–Server Architecture

The system is designed using a client–server architecture based on the TCP/IP protocol stack, which represents one of the most widely adopted communication paradigms in modern computer networks. In this model, the client is responsible for generating the source data, performing Hamming (7,4) encoding, and transmitting the encoded bit stream to the server. The server acts as a passive listener that accepts incoming connections, receives the transmitted data, applies decoding and error-correction algorithms, and reconstructs the original information.

This architecture clearly separates the roles of data generation and data processing at the two endpoints, thereby simplifying system organization and improving modularity. Furthermore, implementing the model over a LAN/Wi-Fi network using TCP sockets enables realistic experimentation under practical networking conditions. Although TCP already provides reliability through acknowledgments and retransmissions, the integration of Hamming coding at the application layer demonstrates how additional bit-level error control can complement transport-layer mechanisms. This layered approach allows learners to understand the interaction between protocol layers and the benefits of combining ARQ and FEC techniques.

2.1.2. Transmission Procedure

The data transmission procedure consists of a sequence of well-defined steps that reflect the complete communication process. First, the server initializes a socket, binds it to a specific IP address and port number, and listens for incoming connection requests. Next, the client initiates a TCP connection using the standard three-way handshake mechanism to ensure reliable session establishment.

Once the connection is established, input data—such as text messages—are converted into an 8-bit binary representation (e.g., ASCII encoding) and segmented into 4-bit blocks. Each 4-bit block is then encoded using the Hamming (7,4) algorithm, generating a 7-bit codeword that contains both data and parity bits. The encoded sequence is transmitted over the TCP connection. Upon reception, the server processes each codeword, computes the syndrome to detect potential single-bit errors, performs correction if necessary, and reconstructs the original binary sequence before converting it back to its initial format.

This procedure illustrates the entire lifecycle of data communication, including generation, encoding, transmission, controlled error introduction, decoding, correction, and final recovery at the receiver side.

2.2. Hamming (7,4) Error-Correcting Code

2.2.1. Code Structure

The Hamming (7,4) code maps four information bits into a seven-bit codeword by adding three parity bits. A codeword is represented as

$$c = (p_1, p_2, d_1, p_3, d_2, d_3, d_4) \quad (1)$$

where di denote the data bits and pi denote the parity bits, computed as

$$p_1 = d_1 \oplus d_2 \oplus d_4$$
$$p_2 = d_1 \oplus d_3 \oplus d_4$$
$$p_3 = d_2 \oplus d_3 \oplus d_4 \qquad (2)$$

with ⊕\oplus ⊕ denoting modulo-2 addition.

2.2.2. Encoding, Error Injection, and Decoding

At the transmitter, input data are divided into 4-bit blocks and encoded into 7-bit codewords using the Hamming (7,4) scheme. To simulate channel noise, random bit errors are introduced according to a predefined error probability.

At the receiver, each received codeword is checked using the parity-check matrix to compute the syndrome vector. If the syndrome is non-zero, the error position is identified and the erroneous bit is flipped to recover the original codeword.

2.2.3. Single-Bit Error Correction

The Hamming (7,4) code is capable of correcting any single-bit error and detecting double-bit errors. The syndrome vector directly indicates the error location, enabling automatic recovery without retransmission.

2.3. Proposed Simulation Framework

2.3.1. System Architecture

The proposed simulation framework is organized into three clearly defined functional modules to ensure modularity, clarity, and ease of experimentation.

Client module: This module is responsible for generating the source data, such as user-input text messages or predefined test sequences. The data are first converted into binary form and segmented into 4-bit blocks. Each block is then encoded using the Hamming (7,4) algorithm to produce 7-bit codewords containing both data and parity bits. Finally, the encoded bit stream is transmitted to the server via TCP/IP sockets.

Channel module: This module simulates the effect of transmission noise. It introduces controlled random bit errors into the encoded sequence according to a predefined error probability. By adjusting this probability, different noise levels can be emulated, enabling systematic performance evaluation.

Server module: The server receives the transmitted data, processes each 7-bit codeword, computes the syndrome, detects potential single-bit errors, performs correction when applicable, and reconstructs the original data sequence.

This modular architecture promotes flexibility and extensibility. For example, the Hamming (7,4) encoder–decoder pair can be replaced with more powerful coding schemes, such as BCH or Reed–Solomon codes, in advanced laboratory exercises without altering the overall communication structure.

2.3.2. Data Flow

The overall data flow follows a structured pipeline: data generation, binary conversion, segmentation into 4-bit blocks, Hamming (7,4) encoding, random error injection in the channel module, TCP/IP transmission, decoding at the server, single-bit error correction, and final reconstruction of the original information. This sequential process clearly illustrates the complete lifecycle of data within the simulation environment, from source creation to reliable recovery.

2.3.3. Error Channel Model

The transmission channel is modeled as a Binary Symmetric Channel (BSC), where each transmitted bit is independently flipped with probability p. This probabilistic model provides a simple yet effective abstraction for evaluating the error-correction capability of the Hamming (7,4) code. Although it does not capture correlated burst errors, multipath fading, or time-varying interference observed in real wireless channels, it is well suited for controlled educational experiments. Moreover, the framework is designed to be extensible, allowing future integration of more advanced channel models, such as the Gilbert–Elliott burst-error model or fading channel simulations, to support higher-level research and instructional activities.

3. Experimental Setup and Results

This section describes the simulation environment, evaluation methodology, and experimental observations obtained from the TCP/IP-based data transmission system integrated with the Hamming (7,4) code. The primary objective is to provide a visual and intuitive platform for teaching error-correcting code (ECC) principles, allowing learners to observe the impact of channel noise and the effectiveness of single-bit error correction at the bit level. Rather than reproducing complex real-world network dynamics, the model focuses on controlled experimentation, clarity of demonstration, and repeatability of results under adjustable noise conditions.

3.1. Simulation Environment

3.1.1. Software Configuration

The system is implemented using a client–server architecture built upon the TCP/IP protocol stack. The client module performs binary conversion and Hamming (7,4) encoding before transmitting the encoded bit stream through a simulated noisy channel. The server module receives the data via TCP sockets, applies syndrome-based decoding, corrects single-bit errors when detected, and reconstructs the original information.

The entire software framework is developed in Python using the built-in socket library for network communication. Additional modules are employed for binary processing and random error generation. The program can be executed either on a single computer (using the loopback interface for demonstration purposes) or on two separate computers connected through a LAN or Wi-Fi network. This flexibility enables both classroom demonstrations and laboratory practice sessions.

3.1.2. Noise Model

The transmission channel is modeled as a Binary Symmetric Channel (BSC), where each transmitted bit is independently inverted with probability p. By varying p, different noise levels can be simulated, enabling quantitative evaluation of error-correction performance under mild to moderate disturbance conditions.

Although the BSC does not represent burst-error behavior, multipath fading, or time-varying interference commonly observed in wireless systems, it offers a mathematically simple and experimentally controllable framework. Its independence assumption makes it particularly suitable for analyzing the correction capability of single-error-correcting block codes such as Hamming (7,4). Furthermore, the adjustable error probability allows students to directly observe how increasing noise levels affect decoding success rates, thereby reinforcing theoretical concepts through practical experimentation.

3.1.3. Simulation Parameters

The main simulation parameters are:

1. Data size: 50 kB
2. Block size: 4 bits
3. Codeword length: 7 bits
4. Number of iterations: 50 per noise level
5. Bit error probability: $p \in \{10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}\}$

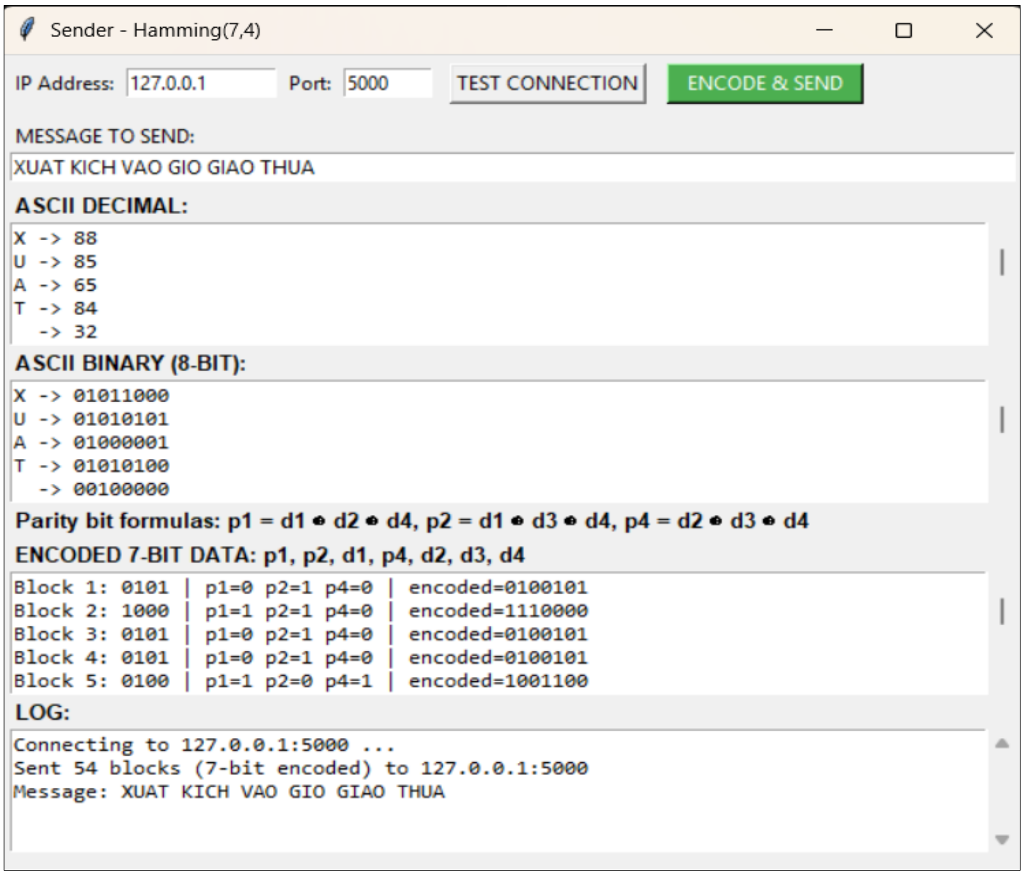
Higher error probabilities are used only for laboratorydemonstrations and do not represent real network conditions.

3.1.4. Graphical User Interface

To support educational objectives and provide intuitive visualization of error-correcting mechanisms, the simulation system is equipped with graphical user interfaces for both the transmitter (client) and receiver (server). The interfaces allow students to monitor the entire bit-level data processing flow in real time.

A. Transmitter (Client) Interface

Figure 1 presents the graphical user interface (GUI) of the transmitter (client) module developed for the Hamming (7,4)-based data transmission system. The interface is designed to provide a clear, step-by-step visualization of the entire encoding procedure, allowing users to observe how input data are transformed before transmission.



```
MESSAGE TO SEND:
XUAT KICH VAO GIO GIAO THUA
ASCII DECIMAL:
X -> 88
U -> 85
A -> 65
T -> 84
  -> 32
ASCII BINARY (8-BIT):
X -> 01011000
U -> 01010101
A -> 01000001
T -> 01010100
  -> 00100000
Parity bit formulas: p1 = d1 ⊕ d2 ⊕ d4, p2 = d1 ⊕ d3 ⊕ d4, p4 = d2 ⊕ d3 ⊕ d4
ENCODED 7-BIT DATA: p1, p2, d1, p4, d2, d3, d4
Block 1: 0101 | p1=0 p2=1 p4=0 | encoded=0100101
Block 2: 1000 | p1=1 p2=1 p4=0 | encoded=1110000
Block 3: 0101 | p1=0 p2=1 p4=0 | encoded=0100101
Block 4: 0101 | p1=0 p2=1 p4=0 | encoded=0100101
Block 5: 0100 | p1=1 p2=0 p4=1 | encoded=1001100
LOG:
Connecting to 127.0.0.1:5000 ...
Sent 54 blocks (7-bit encoded) to 127.0.0.1:5000
Message: XUAT KICH VAO GIO GIAO THUA
```

Fig 1: Graphical user interface of the transmitter implementing Hamming (7,4) encoding and TCP/IP transmission.

At the top of the interface, the network configuration panel displays the IP address and port number (e.g., 127.0.0.1:5000), together with control buttons such as “TEST CONNECTION” and “ENCODE & SEND.” These controls allow users to verify socket connectivity and initiate the encoding and transmission process. This design helps demonstrate how application-layer processing integrates with TCP/IP communication.

The MESSAGE TO SEND field allows users to input ASCII text (e.g., “XUAT KICH VAO GIO GIAO THUA”). Once entered, the system automatically converts each character into its corresponding ASCII decimal value, which is displayed in a dedicated panel. For example, the character ‘X’ is shown with its decimal ASCII code, followed by ‘U’, ‘A’, ‘T’, and so on.

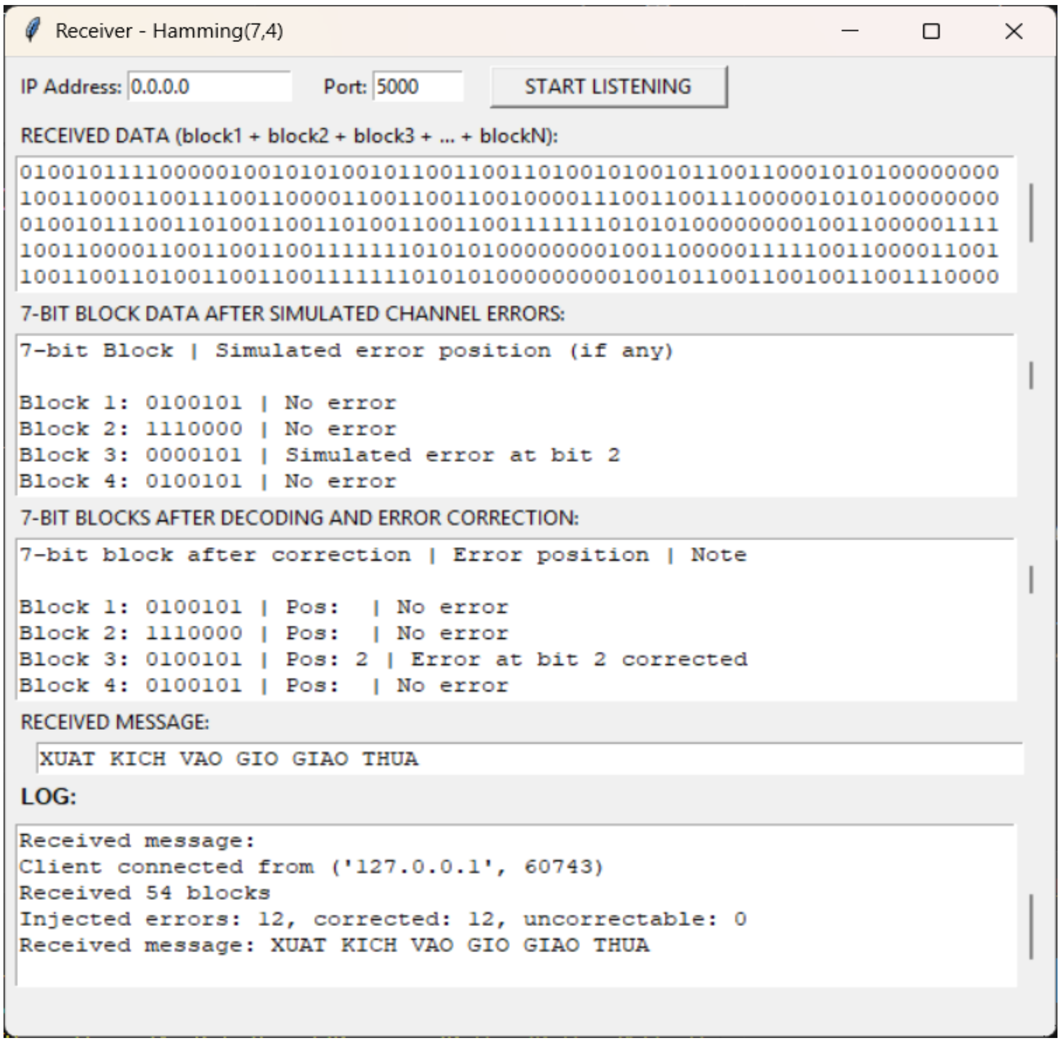
Next, the interface presents the 8-bit ASCII binary representation of each character. This step enables students to clearly observe how textual data are represented at the binary level before channel coding is applied.

The binary stream is then segmented into 4-bit data blocks (d1, d2, d3, d4). For each block, the interface explicitly shows the calculation of parity bits using the Hamming (7,4) formulas:

$$p_1 = d_1 \oplus d_2 \oplus d_4$$
$$p_2 = d_1 \oplus d_3 \oplus d_4$$
$$p_3 = d_2 \oplus d_3 \oplus d_4 \quad (3)$$

The resulting 7-bit encoded codeword (p1, p2, d1, p4, d2, d3, d4) is displayed alongside each original 4-bit block. This detailed presentation allows students to verify parity-bit computation and understand the structural arrangement of Hamming codewords.
Finally, the lower console area logs connection status and transmission activity, indicating successful connection establishment and the number of encoded blocks sent to the receiver. This comprehensive visualization ensures that learners can trace every stage of the encoding and transmission process from message input to TCP/IP data delivery.

B. Receiver (Server) Interface
Figure 2 illustrates the graphical user interface (GUI) of the receiver (server) module in the proposed Hamming (7,4)-based transmission system. This interface is designed to provide a transparent and step-by-step visualization of the decoding and error-correction process after data are received from the transmitter.


Receiver - Hamming(7,4)
IP Address: 0.0.0.0
Port: 5000
START LISTENING
RECEIVED DATA (block1 + block2 + block3 + ... + blockN):
7-BIT BLOCK DATA AFTER SIMULATED CHANNEL ERRORS:
7-BIT BLOCKS AFTER DECODING AND ERROR CORRECTION:
RECEIVED MESSAGE:
LOG:

```
01001011110000010010101001011001100110100101001011001100010101000000000
10011000110011100110000110011001100100001110011001110000010101000000000
01001011100110100110011010011001100111111010101000000000100110000001111
10011000011001100110011111110101010000000001001100000111110011000011001
10011001101001100110011111110101010000000000100101100110010011001110000
```

```
7-bit Block | Simulated error position (if any)

Block 1: 0100101 | No error
Block 2: 1110000 | No error
Block 3: 0000101 | Simulated error at bit 2
Block 4: 0100101 | No error
```

```
7-bit block after correction | Error position | Note

Block 1: 0100101 | Pos:   | No error
Block 2: 1110000 | Pos:   | No error
Block 3: 0100101 | Pos: 2 | Error at bit 2 corrected
Block 4: 0100101 | Pos:   | No error
```

```
XUAT KICH VAO GIO GIAO THUA
```

```
Received message:
Client connected from ('127.0.0.1', 60743)
Received 54 blocks
Injected errors: 12, corrected: 12, uncorrectable: 0
Received message: XUAT KICH VAO GIO GIAO THUA
```

Fig 2: Graphical user interface of the receiver implementing error injection, decoding, and Hamming (7,4) error correction.

At the top of the interface, the network configuration panel displays the IP address (e.g., 0.0.0.0) and port number (5000), along with the "START LISTENING" button. When activated, the server initializes a socket, binds to the specified port, and waits for incoming TCP connections. Once a client connects, the system logs the connection details, including the client's IP address and port number.
The RECEIVED DATA (block1 + block2 + … + blockN) section displays the complete sequence of 7-bit encoded blocks transmitted from the client. This stream represents the Hamming (7,4) codewords prior to decoding.
The next section, "7-BIT BLOCK DATA AFTER SIMULATED CHANNEL ERRORS," shows the encoded blocks after the Binary Symmetric Channel model has injected random bit errors. For each block, the interface indicates whether an error has occurred and specifies the bit position of the injected error (if any). For example, the display may show "Simulated error at bit 2," enabling users to track how noise affects individual codewords.
In the "7-BIT BLOCKS AFTER DECODING AND ERROR CORRECTION" section, the system computes the error syndrome for each received block. Based on the syndrome value, the decoder determines the error position, corrects the erroneous bit when a single-bit error is detected, and confirms successful recovery (e.g., "Error at bit 2 corrected" or "No error"). Both the detected error position and the correction result are explicitly displayed.
Finally, the RECEIVED MESSAGE field presents the fully reconstructed ASCII text after decoding and correction. The log panel summarizes key statistics, including the number of received blocks, total injected errors, number of corrected errors, and uncorrectable cases (if any).
By presenting corrupted blocks, detected error positions, corrected codewords, and the final recovered message in a

structured format, the interface enables students to clearly visualize the complete lifecycle of error detection and correction in a Hamming (7,4) system operating over TCP/IP.

C. Educational Role of the Graphical Interface

The integration of graphical interfaces transforms the system from a purely algorithmic simulator into a comprehensive educational tool. Students can:

Observe the transformation of data from ASCII → binary → codewords;

Visualize the impact of noise on individual bits;

Verify syndrome computation and single-bit error correction;

Understand the relationship between bit error probability, BER, and ECC performance.

Consequently, the system functions as a virtual laboratory for courses in digital communications and data transmission principles.

3.2. Performance Metrics

The performance of the proposed transmission system is evaluated using four metrics:

Bit Error Rate (BER): Measured at the receiver with and without Hamming (7,4) coding.

Error correction success rate: Reflects the ability of the system to correctly detect and correct single-bit errors.

Coding overhead: Represents the additional bandwidth required due to redundancy.

Processing latency: The extra delay caused by encoding and decoding operations, excluding TCP retransmission and congestion control.

3.3. Results and Discussion

3.3.1. Simulation Results

To evaluate the effectiveness of the proposed system, simulations were conducted under different channel noise levels using the Binary Symmetric Channel (BSC) model. For each bit error probability ppp, the experiment was repeated 50 times, and the average results were recorded. The evaluation metrics include:

BER (without ECC): Measured bit error rate before applying error correction.

BER (with Hamming): Residual bit error rate after decoding and correction.

Error correction success rate: Percentage of corrupted 7-bit blocks successfully corrected (single-bit errors only).

The averaged results are summarized in Table 1.

Table 1: BER and Error-Correction Performance of Hamming (7,4)

Bit error probability p	BER (without ECC)	BER (with Hamming)	Error correction success rate
10^{-5}	1.01×10^{-5}	0	100%
10^{-4}	9.9×10^{-5}	8.7×10^{-7}	99.9%
10^{-3}	1.02×10^{-3}	1.8×10^{-5}	99.3%
10^{-2}	9.8×10^{-3}	2.6×10^{-4}	96.8%

The results show that the measured BER without ECC closely approximates the theoretical bit-flip probability p, validating the correctness of the BSC implementation. After applying Hamming (7,4) decoding, the residual BER is significantly reduced, particularly at low and moderate noise levels.

At $p=10^{-5}$, all single-bit errors are successfully corrected, resulting in zero residual BER in the observed runs. For $p=10^{-4}$ and 10^{-3}, the correction success rate remains above 99%, and the residual BER decreases by approximately one to two orders of magnitude compared to the uncoded case.

When the noise level increases to $p=10^{-2}$, performance degradation becomes more noticeable. This is expected, as the probability of multiple-bit errors within a 7-bit codeword increases, exceeding the single-error correction capability of the Hamming (7,4) code. Nevertheless, the system still achieves substantial BER reduction compared to transmission without ECC.

Overall, the simulation results are consistent with theoretical expectations and confirm that Hamming (7,4) provides effective single-bit error correction under moderate noise conditions while maintaining low computational complexity.

3.3.2. Comparison With and Without ECC

Without ECC, the BER at the receiver is approximately equal to the channel BER. With Hamming (7,4) coding, the BER is reduced by one to two orders of magnitude for $p \leq 10^{-3}$, demonstrating the role of ECC in improving transmission reliability.

3.3.3. Cost–Benefit Analysis

The Hamming (7,4) code introduces 75% data overhead and 5–8% additional processing latency. Nevertheless, the resulting improvement in reliability is significant under moderate noise conditions. In an educational context, this trade-off is acceptable and valuable for illustrating bit-level error detection and correction mechanisms.

3.3.4. Scope of Application

In practical TCP/IP networks, bit-level errors rarely occur at high rates, and TCP already provides error detection and retransmission mechanisms. Therefore, the proposed model is not intended for direct deployment in real-world systems. Instead, it serves as an educational platform for illustrating ECC principles, observing noise effects, and practicing the design of error-resilient transmission systems.

The modular architecture also enables extension to more powerful codes such as BCH or Reed–Solomon in advanced laboratory exercises. The experimental results are consistent with the theoretical properties of Hamming codes and validate the correctness of the simulation framework.

4. Conclusion

This study developed and simulated a TCP/IP-based data transmission system integrated with the Hamming (7,4) error-correcting code using a client–server architecture. Rather than proposing a new coding algorithm, the primary contribution lies in building a visual, easy-to-implement, and extensible simulation platform that supports teaching fundamental concepts in digital communications, computer networks, and channel coding.

Experimental results demonstrate that Hamming (7,4) effectively corrects single-bit errors under moderate noise conditions, reducing the bit error rate by one to two orders of magnitude compared with uncoded transmission. These results provide clear quantitative evidence of how forward error correction improves reliability.

The model has certain limitations. The channel is represented by a Binary Symmetric Channel (BSC) with independent bit errors, which does not reflect burst errors or fading effects. Additionally, the redundancy introduced by Hamming (7,4) limits bandwidth efficiency. However, these constraints are pedagogically meaningful, highlighting the trade-offs among reliability, bandwidth, and complexity.

Future work will extend the framework by incorporating more realistic channel models and comparing Hamming codes with stronger schemes such as BCH and Reed–Solomon to enhance both teaching and research applications.

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