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Development of a Radio Data Transmission Channel Model to Ensure Train Safety

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Abstract

This study examines the principles of data transmission via a radio channel to ensure the secure dissemination of information between rolling stock and the Radio Block Center (RBC). Experimental measurements were conducted to determine channel throughput, packet transmission time, and packet loss in a radio network. Interaction with a train over a digital communication channel was used to collect data. The experiment demonstrated that the system meets the requirements for packet transmission time at data rates of up to 1.4 kbps. However, at a load of 1.6–2.0 kbps, the packet transmission time becomes unacceptably high, accompanied by an in-crease in the packet loss rate. To address the issues identified during the experiment, a model was developed to evaluate the characteristics of packet data transmission channels in a TETRA standard digital radio communication network. The resulting quantitative data and plots confirm the validity of the proposed data transmission channel model for TETRA. For further optimization, aimed at maintaining communication quality, the need to implement additional error correction mechanisms was established. The authors have chosen the use of more powerful error-correcting codes as one of the solutions, which will help correct errors caused by noise and protect the transmitted data. The choice of coding method to ensure higher noise immunity under intense electromagnetic interference

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from traction substations and overhead contact lines was based on a comparative analysis of coding techniques used in communication systems.

Keywords: Railway Automation Systems, Train Control System, Digital Channel, Packet Transmission Time, Radio Network, Bit Error Rate, Signal-To-Noise Ratio.

1 Introduction

In the Concept for the Development of the Transport and Logistics Potential of the Republic of Kazakhstan until 2030 and the Development Strategy of JSC "NC "Kazakhstan Temir Zholy" until 2032, key objectives for the transport sector are outlined. These include the implementation of advanced tools and technologies for railway automation, the development of scientific and substantiated requirements to increase the capacity and speed parameters of infrastructure, as well as the justification for creating capacity reserves in the railway network across various directions (Dinesh et al., 2022).

Railway transport in Kazakhstan holds a unique strategic significance, serving as a vital link in the unified economic system (Dei him et al., 2024). It ensures the stable operation of industrial enterprises, the timely delivery of essential goods to the most remote regions of the country, and remains the most accessible mode of transportation for millions of citizens (Kegenbekov et al., 2019).

The operational length of the public railway network is 16.0 thousand kilometers, accounting for 45.3% of the freight turnover within Kazakhstan's transport system.

A key requirement for railway operation is ensuring train traffic safety while maintaining the specified throughput and carrying capacity. This requirement is achieved through the use of railway automation and telemechanics (RAT) devices and systems (Kanagala et al., 2023). RAT devices manage interval train control and ensure traffic safety. Additionally, modern RAT systems enhance productivity and improve labor standards (Sapoznikov et al., 2008; Theeg & Vlasenko, 2020).

Signaling, interlocking, and blocking (SIB) devices play an equally important role in organizing railway transportation. These systems ensure the required capacity, speed, and safety of train operations (Savinov et al., 2021). At the current stage, the railway sector is rapidly evolving, with significant advancements in safety algorithms, increased complexity of electrical circuits, and a growing number of microprocessor systems (Rosenberg et al., 2017). However, despite the measures taken and proposed solutions, numerous challenges persist in the country's railway sector, as over 70% of the existing RAT systems are outdated (Bakhtiyarova & Sansyzbay, 2019). One of the solutions is the implementation of interval train traffic control systems (ITTC), based on the digital radio communication standard, which meets international requirements and can enhance the capacity of mainline network transport corridors in the Republic of Kazakhstan under new economic, technological, and organizational conditions (Sansyzbay et al., 2022).

The further evolution of professional mobile radio communication (PMR) networks is associated with increasing their speed and implementing new data transmission services (Razaque et al., 2023; Sarinova et al., 2021). Currently, most of the operating professional radio networks in European countries are built on traditional systems such as TETRA and GSM-R.

The main issue with the implementation of the GSM-R standard in the Republic of Kazakhstan is the occupation of the required frequency range by the Ministry of Defense of the Republic of Kazakhstan and commercial operators. The issue of freeing the required frequency spectrum for GSM-R for civilian use has been raised multiple times. The frequency range necessary for the TETRA technology is partially used by government agencies for trunking communication. These frequencies are significantly cheaper and less congested (Kegenbekov & Kerimkulova, 2019).

The decision was made by JSC "NC "KTZ" to implement a digital radio communication and data transmission network on the railways of Kazakhstan, based on the trunking radio communication standard TETRA, which is based on the technical solutions and recommendations of the GSM standard (Arvinth, 2024).

In recent years, the construction of new railway lines in Kazakhstan has seen the implementation of RBTC (Radio-based train control system) (Bombardier Transportation), which utilizes continuous data transmission via TETRA radio channels (Bakhtiyarova et al., 2020; Mehta & Dutta 2024). This system has been deployed on recently commissioned lines (Shamanov, 2018). However, the adopted data transmission system from various manufacturers within RBTS frequently experiences malfunctions and operates with insufficient reliability (Mohandas et al., 2024). The most common issues include loss of radio communication, the onboard safety system switching to a protective mode, the inability to connect RBTS during the transition of rolling stock between sections, incorrect operation of the odometry system, and other similar problems.

The aim of this article is to find solutions to the existing issues in RBTC, as well as to conduct testing and research work. To achieve this goal, the authors have addressed the following tasks:

- Conducted a two-stage performance testing of the RBTC system on the Zhetygen–Altynkol section (detailed in (Sansyzbay et al., 2020; Sansyzbay et al., 2024));
- Developed a data transmission channel model using the TETRA standard in Simulink;
- Performed calculations using the CRC encoding method recommended by the CENELEC standard.

2 Experimental Methodology and Results

The ITTC based on the radio channel is one of the newest and most recently implemented railway automation and telemechanics systems in the mainline network of JSC "NC "KTZ".

The RBTC system is a unified complex of safety and train control systems for sections and stations, and consists of the following key components:

- Microprocessor-based centralization system KZ-MPC-MA (Sansyzbay et al., 2024) (including train control systems for sections, as well as equipment for the traffic management center and automated workstations for station dispatchers, central dispatching centers, and signaling personnel);
- Radio blocking center (including the dispatcher’s workstation for inputting speed restrictions, as well as output equipment for determining the train's location);
- Onboard train control and management computer, along with its peripheral devices (Dunaev et al., 2021);
- The subsystems of output devices are connected via an Ethernet network. The connection between the onboard computer and the radio blocking center is established through a TETRA radio channel (Stepanova, 2017).

The block diagram of the interconnection between the main components of the RBTC system is presented in Figure 1.

The practical application of the radio blocking system is considered on the Zhetygen – Altynkol section of the Almaty branch of the mainline network. The practical implementation addresses the issues of communication between the radio blocking center and the TETRA switching center, integration of the radio blocking center with the electrical interlocking systems, modernization of the onboard locomotive equipment, and verification of the algorithms for the operation of both onboard and stationary equipment.

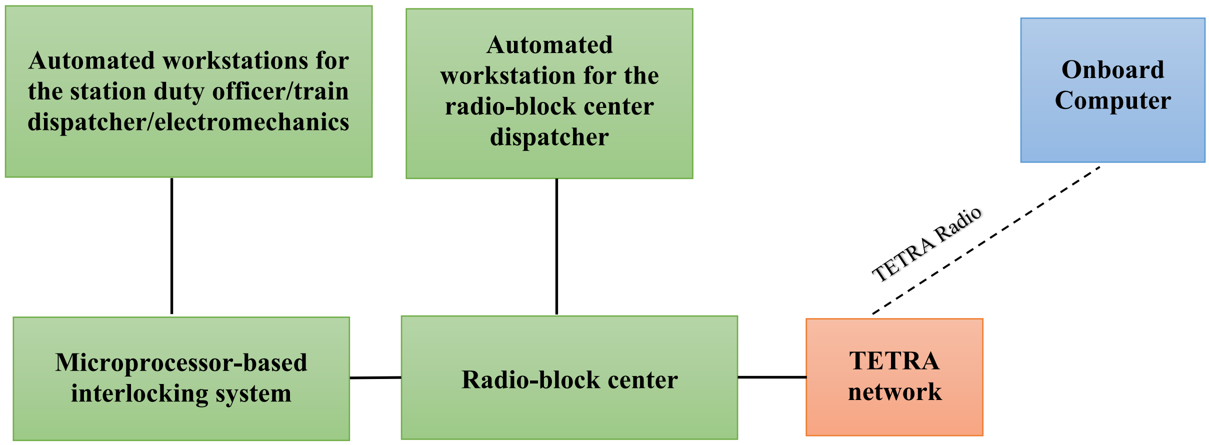


Figure 1: Main Components of the RBTC System

An experiment was conducted to test the system according to the diagram presented in Figure 2 (Sansyzbay et al., 2020).

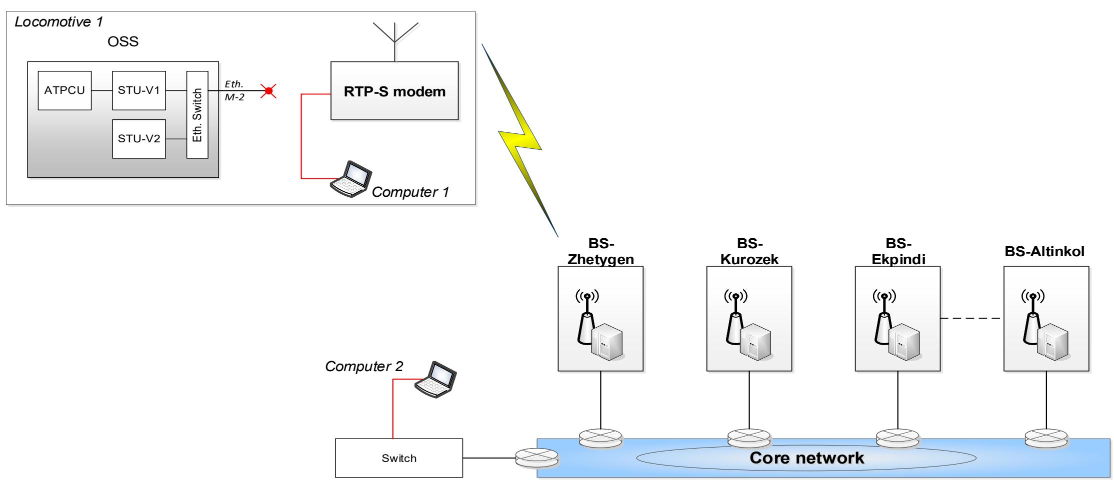


Figure 2: Test model with long ping and UDP packet load test

Computer A is connected to the RTP-S radio modem on the locomotive, while computer B is connected to the TETRA backbone network through a switch at the Zhetygen station's electrical interlocking post.

Both computers are equipped with software ("receiver" on computer B and "transmitter" on computer A) that facilitates the transmission of UDP packets of varying lengths at different speeds. By increasing or decreasing the number of packets, the load on the radio channel is adjusted.

During the experiments, specialized software is run on computers A and B to manage the transmission and reception of UDP packets. The locomotives involved in the experiments are stationary, and no movement is carried out by other locomotives equipped with the RBTC system.

The equipment used in the experiment is shown in Table 1.

Table 1: The Equipment for Conducting the Test

Name	Installation Location	Quantity
RTP-S Data Transmission Modem	Locomotive TE33A with No. 0218, Locomotive TE33A with No. 0261	2
Base Station	EC Post at Zhetygen Station	1
Laptop with Specialized Test Software (Traffic Simulator)	Locomotive TE33A with No. 0218, Locomotive TE33A with No. 0261	2
Laptop with Specialized Test Software (Traffic Simulator)	EC Post at Zhetygen Station	2

During the experiment, alongside other packet data dimensions, the setting shown in Table 2 was used, which is necessary for our further research.

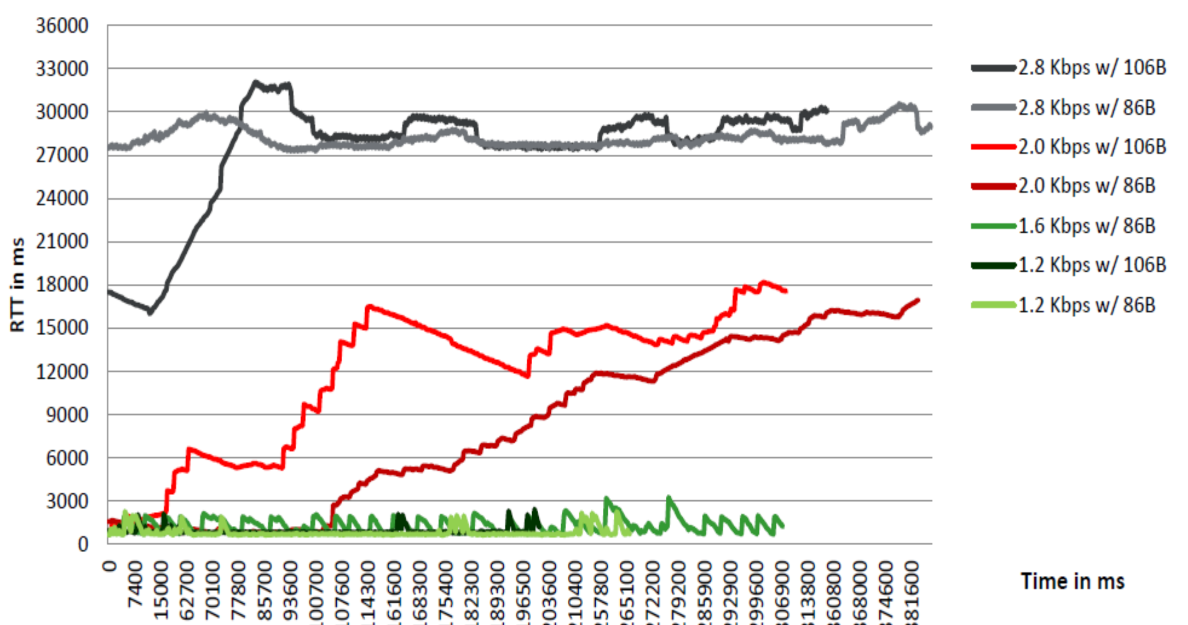
Table 2: The Results Obtained During the Experiment

Packet Size (bytes)	Data Channel Load (kbps)	Test Duration (min)
86	1.2-2.8	105
108	1.2-2.8	30

The measurement results, including data on channel throughput, packet transit time, and packet loss data in the TETRA radio network, are presented in Figure 3 for packet transmission times of 86 and 108 bytes at speeds ranging from 1.2 to 2.8 kbps.

As shown in the graphs in Figure 3, for 108-byte packets, the experiments produced the following results:

- At speeds of 1.2-1.6 kbps, the packet transmission time varies from 1 to 3 seconds throughout the entire test duration;
- At a speed of 2.0 kbps, the transit time reaches 18 seconds, with the transit time increasing over the course of the experiment;
- At a speed of 2.8 kbps, the packet transmission time is approximately 30 seconds. For 108-byte packets, the transmission time was around 18 seconds at the beginning of the test, and then it sharply increased to 32 seconds.



Data Rate (Kbps)	Packet Size (Bytes)	Avg.RTT (s)	%Loss
1.2	86	0.84	0
1.6	86	1.32	0
2.0	86	8.08	0
2.8	86	28.25	29.15
1.2	108	0.91	0
2.0	108	11.62	0
2.8	108	28.25	29.15

Figure 3: Packet Transit Time for 86 and 108-byte Packet

The conducted experiments show that in the TETRA standard digital radio communication system, as the load on the system increases, the packet transit time also in-creases. For transmission speeds up to 1.4 kbps, the system meets the packet transit time requirements. However, starting from a load of 1.6-2.0 kbps, the packet transit time becomes unacceptably long, reaching 30-40 seconds, which does not meet the specified requirements (Sansyzbay et al., 2021).

At the same time, the percentage of lost packets increases (up to 50%), with in-stances of multiple consecutive packet losses observed.

In addition, during the implementation of this system, experimental studies were conducted for different packet sizes, and the identified issues were addressed. In works (Sansyzbay et al., 2024), it was recorded that as a result of the experiments, instances of communication loss between the onboard safety system and the modem were observed. The main issue was that after the connection was restored, the modem failed to receive data, which led to the repeated activation of the train's emergency braking system.

It is known that emergency braking can have negative consequences. First, it poses a threat to the safety of passengers and the integrity of cargo. Second, an emergency stop of the train causes delays for subsequent trains, disrupting the entire transport network, leading to financial losses, and creating additional organizational problems. Third, sudden braking has a detrimental effect on the technical condition of the rolling stock, increasing the likelihood of requiring repairs.

3 Solutions

To resolve the issue identified during the testing of the RBTC system on the Zhetygen-Altynkol section, the article proposes a model (Figure 4) designed to assess the characteristics of data transmission channels in the TETRA digital radio communication network. The main objective of the study is to develop approaches to eliminate connection losses during data transmission between the onboard safety system and the radio block center by testing the developed model (Mylnikov & Popov, 2016).

The model was constructed in Simulink (MATLAB) using standard blocks from the library. The model includes the following key components: Source, which generates the original data in the form of bit sequences; Convolutional Encoder, which performs data encoding to correct errors; Interleaver, which shuffles the encoded data to im-prove error resistance; Modulator, which modulates the data for transmission through the channel; AWGN Channel, simulating data transmission with the addition of white Gaussian noise; Demodulator, which demodulates the received data at the receiving end; Viterbi Decoder, which performs decoding using the Viterbi algorithm to correct errors; Bit Error Rate (BER) Calculator, which is used to measure the number of errors and evaluate the system's performance.

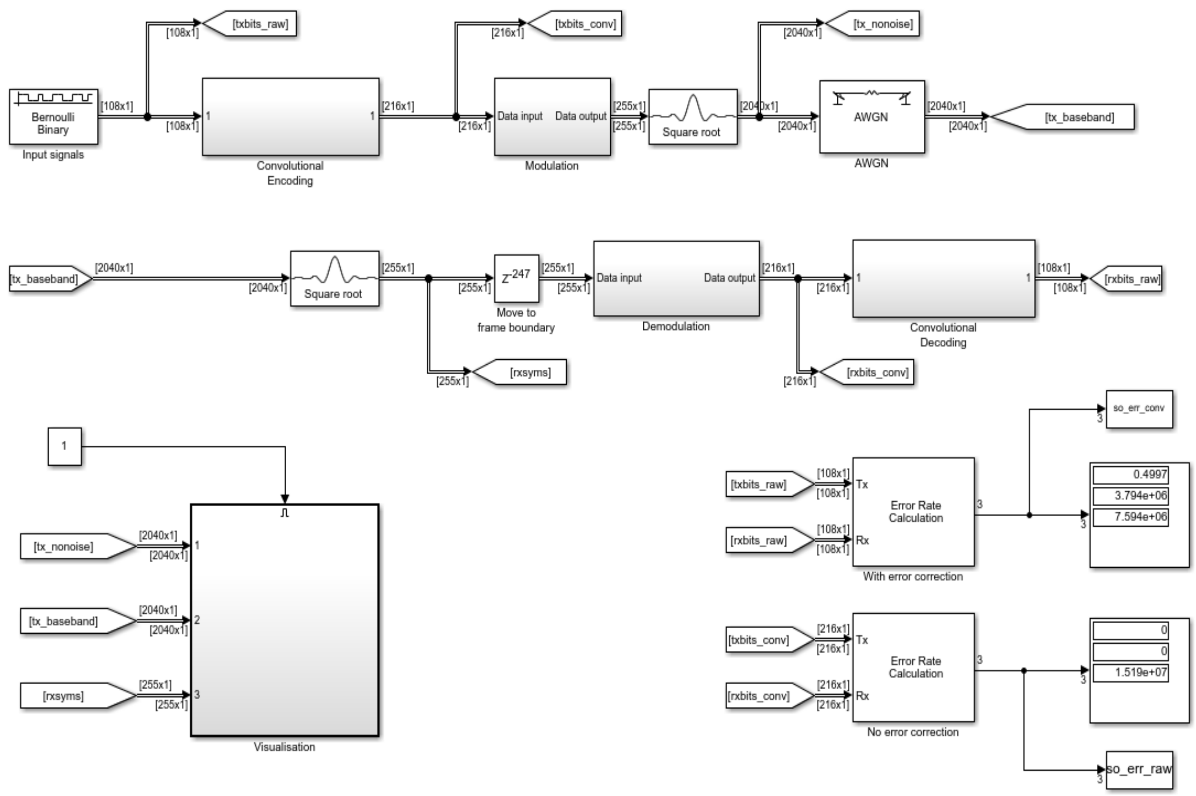


Figure 4: Model of the TETRA Data Transmission Channel

With the provided TETRA model based on DQPSK modulation in the Simulink environment, several types of studies can be conducted related to signal processing, communication systems, and testing various physical layer parameters:

- Study how the noise level affects the quality of the communication, using the bit error rate (ber) indicator, which will help identify critical noise values at which data transmission becomes ineffective;
- Study the characteristics of dqpsk modulation and its performance, with the aim of evaluating the performance and resilience of different modulation types in the presence of real-world interference;
- Evaluate the impact of different error correction methods on the quality of the communication;
- Investigate how data transmission over the tetra network using dqpsk affects the energy efficiency of the system, which will allow the development of recommendations for optimizing energy costs;
- Assess the impact of various data transmission speeds on system performance and determine the maximum data transmission rate at which the tetra system maintains stable communication;
- Assess the impact of the handover process on the stability and efficiency of the communication;
- Compare the performance and robustness of different modulation schemes that could be used in the tetra standard;
- Analyze the system's behavior under various real-world conditions and evaluate its adaptability.

These directions allow not only the investigation of the model's basic parameters but also its behavior under real-world operating conditions, including the impact on signal quality, modulation performance, and interference resistance (Nikitin, 2023; Penghui et al., 2022).

4 Development of the Model and Results

During the testing of the developed model, a bit sequence with a size of 108 bits was input into the system. This sequence contained information about the actual speed of the train, the braking curve, the distance to the next train, and other parameters.

Each block and element of the model was assigned specific parametric values, and the results were obtained in both graphical and quantitative forms.

During testing, the noise level in the transmission channel varied between 30 dB and 0 dB. The BER (Bit Error Rate) values with and without convolutional correction were determined using the Error Rate Calculation block. The output of the blocks was connected to a display with three indicators, allowing the analysis of performance: BER, Erroneous bits, and Total number of transmitted bits during the simulation. The obtained BER values are presented in Table 3.

Table 3: Results of BER Parameter Calculation

Parameter	BER without Convolutional Coding			BER with Convolutional Coding		
SNR=30dB	0.4997	3.794e+06	7.594e+06	0	0	1.519e+07
SNR=20dB	0.4997	3.794e+06	7.594e+06	0	0	1.519e+07
SNR=20dB	0.4997	3.794e+06	7.594e+06	1.067e-05	162	1.519e+07
SNR=17dB	0.4997	3.794e+06	7.594e+06	6.584e-08	1	1.519e+07
SNR=16dB	0.4997	3.794e+06	7.594e+06	1.054e-06	16	1.519e+07
SNR=15dB	0.4997	3.794e+06	7.594e+06	1.067e-05	162	1.519e+07
SNR=14dB	0.4997	3.794e+06	7.594e+06	7.427e-05	1128	1.519e+07
SNR=13dB	0.4996	3.794e+06	7.594e+06	0.0003642	5532	1.519e+07
SNR=12dB	0.4998	3.795e+06	7.594e+06	0.001319	2.003e+04	1.519e+07
SNR=11dB	0.5	3.797e+06	7.594e+06	0.003724	5.656e+04	1.519e+07
SNR=10dB	0.4999	3.796e+06	7.594e+06	0.008738	1.327e+05	1.519e+07
SNR=9dB	0.5002	3.798e+06	7.594e+06	0.01747	2.654e+05	1.519e+07
SNR=8dB	0.5002	3.799e+06	7.594e+06	0.0308	4.678e+05	1.519e+07
SNR=7dB	0.4998	3.795e+06	7.594e+06	0.04909	7.455e+05	1.519e+07
SNR=6dB	0.4996	3.794e+06	7.594e+06	0.07229	1.098e+06	1.519e+07
SNR=5dB	0.5001	3.798e+06	7.594e+06	0.0998	1.516e+06	1.519e+07
SNR=4dB	0.5	3.797e+06	7.594e+06	0.1308	1.987e+06	1.519e+07
SNR=3dB	0.5003	3.799e+06	7.594e+06	0.1645	1.498e+06	1.519e+07
SNR=2dB	0.5	3.797e+06	7.594e+06	0.1995	3.03e+06	1.519e+07
SNR=1dB	0.5	3.797e+06	7.594e+06	0.2348	3.566e+06	1.519e+07
SNR=0dB	0.4999	3.796e+06	7.594e+06	0.2694	4.092e+06	1.519e+07

The obtained results demonstrate how the signal-to-noise ratio (SNR) affects the bit error rate (BER) for cases with and without convolutional coding and serve as proof of the correctness of the constructed model.

The provided data show how changes in the signal-to-noise ratio affect the bit error probability in the data transmission system. In the absence of convolutional coding, the bit error probability remains around 0.5, indicating almost random data transmission. This is due to the fact that the lack of error correction makes the system highly sensitive to noise.

With the use of convolutional coding, a significant improvement in data trans-mission quality is observed. At high SNR values, the bit error probability becomes extremely low, indicating nearly error-free data transmission. As the SNR decreases, the error probability gradually increases, but it remains much lower than in the system without coding.

At low SNR values, the impact of noise becomes more noticeable, leading to an increase in error probability even with convolutional coding. However, the system with coding demonstrates higher resilience to noise compared to the system without coding (Qingmiao et al., 2023).

Thus, the use of convolutional coding significantly improves data transmission quality, especially under high SNR conditions. However, as SNR decreases, the effectiveness of coding gradually diminishes, and additional measures such as increasing signal power or employing more advanced error correction methods may be required to maintain transmission quality.

The analysis of the dependence of the bit error rate on the signal-to-noise ratio reveals the ranges in which communication operates most efficiently and helps identify the optimal SNR level for the system. At an SNR of 16 dB or higher, the error probability with convolutional correction becomes extremely low, reaching values on the order of 1.054e-06. This indicates an almost error-free transmission and high reliability of data transfer. Within the range of 17 to 30 dB, the error probability is nearly zero, highlighting the optimal operating conditions of the communication channel.

As the SNR decreases from 15 to 8 dB, a gradual increase in the BER is observed. For instance, at an SNR of 15 dB, the error probability is 1.067e-05, while at an SNR of 8 dB, it rises to 0.0308. Despite this growth, the communication quality remains acceptable for most tasks within the range of 12 to 15 dB, particularly when additional error correction mechanisms are employed.

At SNR levels below 8 dB, a sharp increase in the error probability is observed. For instance, at an SNR of 7 dB, the BER reaches 0.04909, and as the SNR further decreases to 4 dB or lower, the error probability rises to 0.1308 or higher. These conditions become unsuitable for reliable data transmission, as the increase in BER is accompanied by a significant decline in system efficiency.

The optimal SNR level for stable system operation can be considered to be values equal to or greater than 16 dB. At this level, the probability of errors is minimal, ensuring high reliability of communication. SNR levels between 12 and 15 dB are also acceptable, although they require greater noise resilience through signal amplification or the use of powerful error correction algorithms. For SNR values below 12 dB, additional measures should be implemented to compensate for the deterioration of communication quality.

It should be noted that the presented model of the TETRA physical layer channel includes some simplifications: convolutional coding is applied, which differs from that specified in the EN 300 392-2 standard, and block coding is absent. However, this simplification does not affect the correctness of the obtained results. The model functions correctly as it demonstrates the expected patterns: at high SNR, error correction effectively reduces BER, while at low SNR values, the impact of noise becomes critical. The optimal SNR range is considered to be values above 16 dB, as mentioned earlier, since within this range, error correction ensures reliable data transmission with minimal losses.

5 Discussion

In addition to the quantitative BER values, the developed model also provides a graphical representation of the resulting signal, as discussed earlier. Using the output signal graphs obtained under different noise levels, shown in Figures 5 and 6, an analysis of the characteristics of the modulated signal was conducted (Pépin & Vigliotti, 2016; Lopez & Aguado, 2015). Each graph will be examined in detail to interpret its features and identify potential issues more comprehensively.

In the first graph (Spectrum Plot) in both Figures 5 and 6, the signal spectrum is displayed:

a) at SNR = 20 dB, as shown in Figure 5:

- The spectrum displays well-defined peaks and a narrower frequency band. This indicates that the signal is transmitted with minimal noise interference;
- The snr is sufficiently high, as evidenced by the absence of significant noise spikes outside the band;
- The good spectral profile indicates efficient use of the frequency band and high-quality transmission.

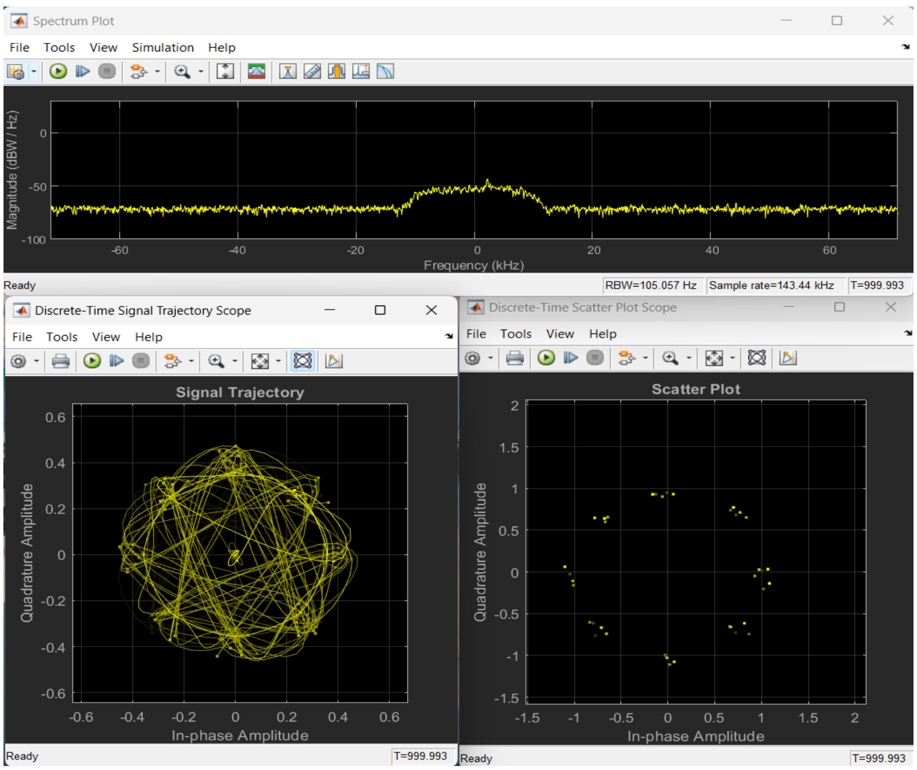


Figure 5: Resulting Signal Characteristics at SNR = 20 dB

b) at SNR = 0 dB, as shown in Figure 6:

- The spectrum becomes more "blurred," with a noticeable increase in noise. This is due to the noise starting to dominate over the useful signal;
- The increase in energy beyond the main frequency band indicates strong interference and a decline in transmission quality;
- The degradation of the spectral quality could lead to interference with other signals in a real communication system.

In the second graph (Discrete-Time Signal Trajectory Scope) in both Figures 5 and 6, the signal trajectory is shown:

a) at SNR = 20 dB, according to Figure 5:

- The signal trajectory describes a neat shape, which is close to an ideal circle (for modulation, e.g., qpsk or qam);

- This indicates that distortions are minimal, and the signal passes through the communication channel with good recovery of its phase-amplitude characteristics.

b) at SNR = 0 dB, according to Figure 6:

- The trajectory becomes chaotic, with a large spread. This is due to noise introducing significant distortions to the signal;
- Such a trajectory is typical for cases where the useful signal is "overlapped" by noise, leading to degraded demodulation.

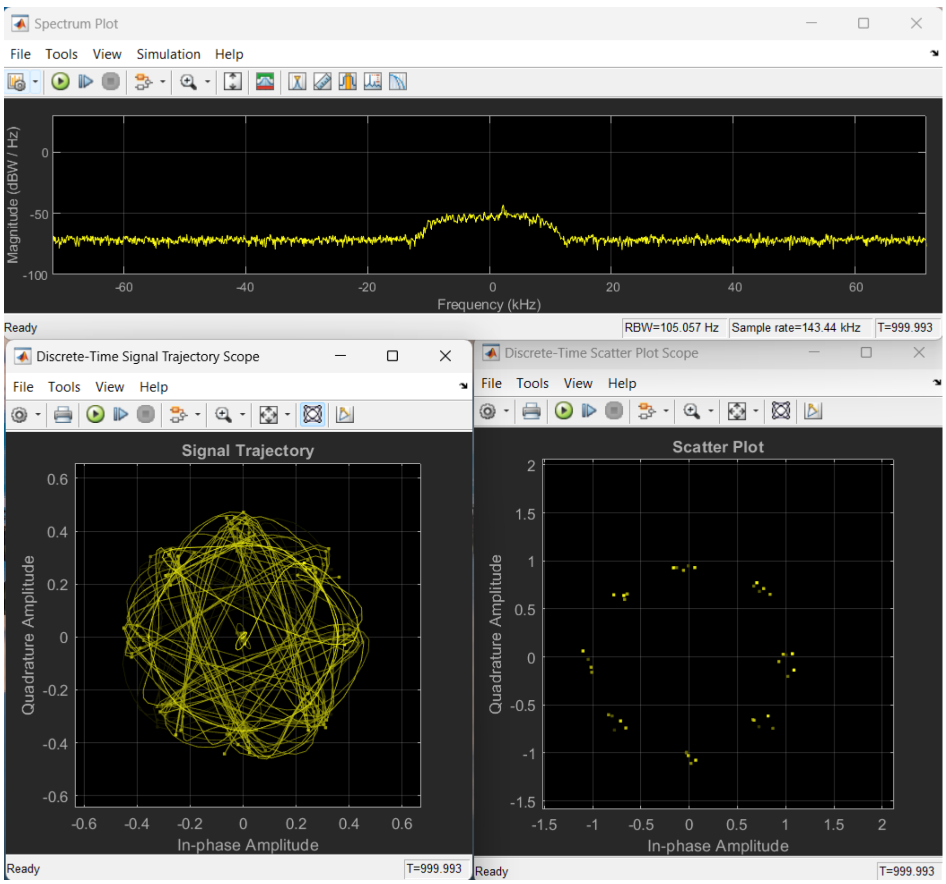


Figure 6: Resulting signal characteristics at SNR = 0 dB

In the third graph (Discrete-Time Scatter Plot Scope) in both Figures 5 and 6, the constellation diagram is shown. The constellation diagram is a key indicator of the quality of digital modulation, as it reflects the position of the signal symbols after de-modulation:

a) at SNR = 20 dB, as shown in Figure 5:

- The constellation points are clearly clustered in narrow regions around the expected positions. This indicates a high level of symbol recovery;
- The signal is almost unaffected by noise, resulting in a minimal probability of errors (low ber).

b) at SNR = 0 dB, as shown in Figure 6:

- The constellation points are widely scattered and deviate from their ideal positions. This is the result of noise, which "mixes" the symbol values.

- This blurring of signals leads to an increase in the probability of errors during demodulation (high ber).

The conclusions and interpretation of the results demonstrate the differences in the operation of the communication channel at various SNR levels. At high SNR values, the channel operates under optimal conditions, ensuring almost zero BER and high transmission efficiency. The constellation diagram in these conditions shows clear and accurate symbols. Under low SNR conditions, the communication channel is subject to significant interference, leading to an increase in error probability and a de-crease in data transmission quality. The signal energy in such conditions is utilized less efficiently, which may cause interference. To maintain the quality of communication in such scenarios, the implementation of additional error correction mechanisms is required.

However, in real-world operating conditions, it is not always possible to maintain a high SNR, which is why it is necessary to improve the signal quality through other means and methods in such environments.

One of the most optimal solutions is the use of more powerful error-correcting codes, which can help correct errors caused by noise and protect the transmitted data.

The most widely used codes for data transmission protection belong to the class of linear codes. Linear codes ensure reliable detection of a specific number of single-bit errors, namely d-1 (where d represents the Hamming distance). Errors beyond this are detected only with a certain probability. In many cases, security codes are required to detect not only independent single-bit errors but also other types of errors. The unsafe transmission systems used (GSM, TETRA, DECT) already incorporate their own error detection mechanisms. The security code should activate in cases where the disruptive influence is so significant that the transmission system's code capabilities are insufficient, or when the transmission system operates with errors. In both cases, it cannot be assumed that only independent single-bit errors will occur.

Modern train control and communication systems (e.g., ETCS, CBTC, RBTC) typically use convolutional codes, turbo codes, and LDPC codes, which provide higher resilience against electromagnetic interference from traction substations and overhead contact lines. These codes are used to protect data from errors and ensure reliable in-formation transmission. Below, Table 4 presents a comparison of the most commonly used methods.

Table 4: Comparison of the Most Commonly used Methods for Coding

Encoding Method	**Error Detection**	**Error Correction**	**Computational Complexity**	**Used in**
CRC	Yes	No	Low	ETCS, CBTC, RBTC
Convolutional Codes	Yes	Yes (Viterbi)	Medium	ETCS (GSM-R, GPRS), CBTC, RBTC
Turbo Codes	Yes	Yes (Iterative)	High	CBTC (LTE, Wi-Fi), RBTC
LDPC	Yes	Yes (Iterative)	Very High	CBTC (5G, Wi-Fi 6), RBTC (LTE-R)

The table 4 shows that the ETCS system primarily uses CRC and convolutional codes, as they are compatible with GSM-R. The CBTC system uses turbo codes and LDPC because they are better suited for Wi-Fi/LTE. In the RBTC system, depending on the technology, either convolutional codes combined with CRC encoding (GSM-R, TETRA) or LDPC (5G/LTE-R) are used. In the RBTC system, which is currently operat-ing on the Zhetygen – Altynkol and Uzen – Bolashak sections of the railway network in Kazakhstan, the TETRA standard is applied. Therefore, in this part of the work, calculations were made using the CRC encoding method. This method, recommended by the CENELEC standard, uses polynomial arithmetic to compute the checksum, meaning binary numbers are represented as formal polynomials with binary coefficients.

This method ensures the detection of single-bit errors, double-bit errors, errors of arbitrary odd multiplicity, as well as burst errors, which are distortions of consecutive bits within a packet whose length does not exceed the length of the divisor.

The structure of the transmitted data is as shown in Figure 7.

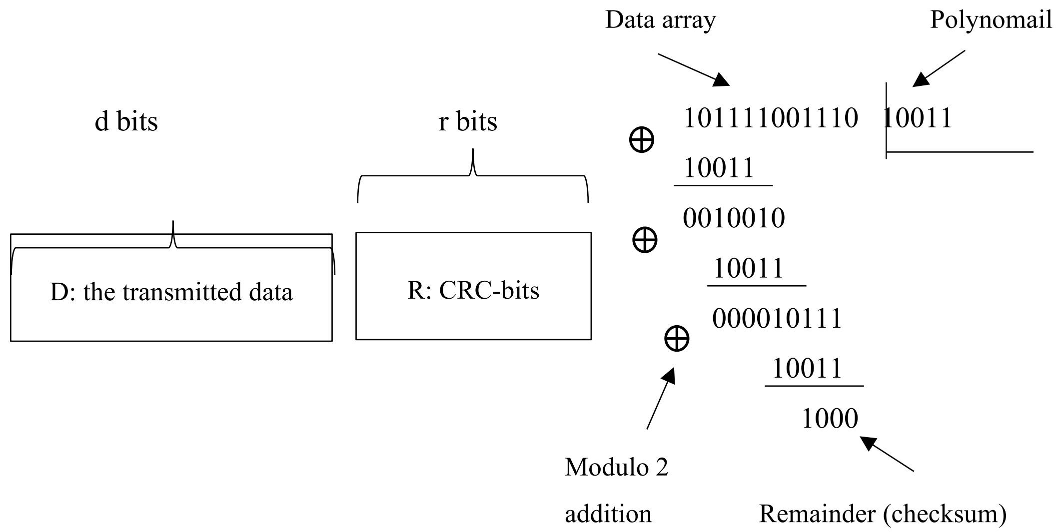


Figure 7: The structure of the transmitted data

The initial word is extracted from the file, which represents a bit, byte, or other unit of data. If the most significant bit of this word is «1», it is shifted left by one bit, followed by a bitwise XOR operation with the generator polynomial. If the most significant bit is «0», no XOR operation is performed after the shift. During the shift, the most significant bit is lost, and the least significant bit is replaced with the next bit from the file. This process continues until all bits from the file are read. Once processing is complete, the remaining value in the word represents the remainder, which is interpreted as the CRC checksum.

Let's consider an example of data transmission. A stationary device using a local radio channel sends messages sequentially to locomotives within its coverage area and receives acknowledgment receipts from the locomotives confirming the reception of the messages. Suppose the message has a length of M=108 bits of content information in the telegram sent to the locomotive. Additionally, each transmission is encoded using a CRC method of length N=48 (with a detection capability of $3.6 \cdot 10^{-15}$). The message is sent to the train over the radio channel at a speed of 900 bits/sec (i.e., 10,800 messages per hour). The transmission process includes a retransmission mechanism and accounting for the delay in receiving data on board due to retransmissions.

A dangerous failure in transmission with retransmissions occurs in the following cases: if an error in the transmission was not detected during the first attempt by the error checking conditions; if the first error was detected but the second was not; or if the first two errors were detected but the third was not, and so on.

The overall effectiveness of applying the CRC code according to the CENELEC EN 50159 standard is evaluated by the probability of an undetected error, 2^{-N}, where N is the bit length of the code. Common values for the failure rate parameter are 10^{-3} and 10^{-4}, which account for the average probability of bit distortion (not necessarily a single-bit error) in the transmitted message. Thus, the error probability (not necessarily a single-bit error) in a message of length M+N can be calculated using the following formula:

$$(M+N)\cdot 10^{-4} \qquad (1)$$

Let's assume a two-channel line with a CRC-8 transmission code, a packet size of 8 bytes, and a CRC 32 protection code (different polynomials in the channels), with message lengths up to 1500 bytes, and the ability to send 5 messages per second.

In communication over a two-channel line, identical distortions in messages in both channels may occur, which are undetectable at the transport level.

To obtain the final result, the probability of distortion of each bit in the messages will be considered as $p_1=10^{-4}$ (section 2.11.2 of GOST 26.205-88 Telemechanics complexes and devices. General specifications).

Let's define the code distance for CRC-8 and a packet length of v = 64 bits (8 bytes) based on Table 5.

Table 5: «Best» Polynomials for HD at given CRC Size and Data Word Length. Underlined Polynomials have been Previously Published as «good» Polynomials

Max length at HD /Polynomial	**CRC Size (bits)**					
	3	**4**	**5**	**6**	**7**	**8**
HD=2	2048+0x5	2048+0x9	2048+0x12	2048+0x33	2048+0x65	2048+0xe7
HD=3	40x5	110x9	260x12	570x33	1200x65	2470xe7
HD=4			100x15	250x23	560x5b	$\boxed{\text{1190x98}}$
HD=5					40x72	90xeb
HD=6…						40x9b

The code distance HD = 4, meaning that the system can detect errors affecting three or fewer arbitrary bits in the packet.

Distortion of four or more arbitrary bits in the packet is undetectable and leads to a hazardous failure (a failure of safety functionality).

The probability of distorting 4 or more bits out of 64 is calculated using the Bernoulli formula

$$P(k) = C_n^k\, p^{\,k}\, q^{n-k},\ k = 0,1,2\ldots n \qquad (2)$$

where C_n^k – is the number of combinations of n taken k at a time and is equal to

$$P_{\geq 4} = 1 - P_{<4} = 1 - (C_{64}^0\, p_1^0\,(1-p_1)^{64-0} + C_{64}^1\, p_1^1\,(1-p_1)^{64-1} + C_{64}^2\, p_1^2\,(1-p_1)^{64-2} + C_{64}^3\, p_1^3\,(1-p_1)^{64-3} = 6{,}32E-11 \qquad (3)$$

Considering that dangerous uncontrollable distortions must occur simultaneously in two consecutive data blocks and must be correct and equivalent, then

$$P_{1+1} = P_{\geq 4}\cdot P_{\geq 4}\cdot P_{cor\_eq} \qquad (4)$$

The first factor in expression (3) defines the probability of distortion of the first packet with a correct CRC8 checksum. The second factor is similarly defined in (Franekova M. et al., 2011).

The third factor defines the probability that the information in both packets (after distortion) will be correct and equivalent not only within the packet but also between them. The probability P_{cor_eq} can take values from 1 to $(1/2)^{v}$, where $(1/2)^{64}$ =5,4$E-20$.

Assuming the worst-case scenario where $P_{cor\_eq} = 1$, we get:

$$P_{1+1} = (6{,}32E - 11) \cdot (6{,}32E - 12) \cdot 1 = 4E - 21 \qquad (5)$$

It should be noted that protecting the entire message with a transport checksum CRC32 will significantly reduce the probability of identical message distortions in both channels.

6 Conclusions

In this work, a data transmission model for the TETRA system was developed to address the issues identified during the experiments. The experiment showed that when transmitting a message of 108 bits at a transmission speed of up to 1.4 kbps, the system meets the packet transmission time requirements. However, starting from a load of 1.6-2.0 kbps, the packet transmission time becomes unacceptably long, reaching 30-40 seconds, which does not meet the required standards. At the same time, the per-centage of lost packets increased (up to 50%), with losses of several consecutive packets being observed.

To assess the impact of the SNR on the BER for cases without convolutional correction and with convolutional correction, the built model was tested. The results revealed that for stable system operation, it is recommended to maintain the SNR at or above 16 dB. For values below 12 dB, more powerful error correction algorithms or signal amplification should be used. The obtained results served as proof of the model's correctness.

Additionally, paths to ensure quality data transmission in conditions where maintaining the required SNR is not possible were considered. The optimal solution in such conditions is the use of more powerful error correction codes, which help correct errors caused by noise and protect the transmitted data.

In this work, a calculation was made using the CRC encoding method recommended by the CENELEC standard. In this method of calculating the checksum, polynomial arithmetic is used, meaning that binary numbers are represented as formal polynomials with binary coefficients. This method guarantees the detection of single and double errors, arbitrary odd-multiple errors, as well as packet-type errors, which manifest as distortions of a sequence of consecutive bits, with the length of the packet not exceeding the length of the divisor.

The results of the calculation demonstrated the effectiveness of applying this encoding method.

7 Author Contributions

All authors made significant contributions to the research conducted on the topic of this article. Laura Tasbolatova developed and tested the data transmission channel model based on the TETRA standard, with the results presented in Section III: Solutions and Section V: Discussion of Results. Kanibek Sansyzbay. conducted experimental testing aimed at identifying issues in data transmission between the onboard safety system and the modem, followed by developing solutions within the RBTC system. The results of these tests are described in Section II: Experimental Methodology and Results. Ulrich Maschek and Marat Orynbet provided consultation to the doctoral candidate during the article's preparation, recommending standards and documents necessary for building the model. Yelena Bakhtiyarova constructed the Test Model with Long Ping and UDP Packet Load Test and calculated the parameters for configuring the blocks involved in data transmission within the TETRA trunked communication system. Aigul Turayeva contributed by formatting the article and conducting grammar, consistency, and logic checks of the presented material. All authors approved the final version of the article.

8 Conflicts of Interest

The authors declare no conflict of interest.

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