UDC 004.41: 621.396:004.7:656.2
DOI: 10.20535/SRIT.2308-8893.2025.3.03

RESEARCH AND DEVELOPMENT OF METHODS TO IMPROVE THE QUALITY OF MOBILE COMMUNICATION AND MOBILE INTERNET IN HIGH-SPEED TRAINS

N.V. SHTEFAN, S.V. ZHIGLO

Abstract. This paper proposes effective methods and means to enhance the quality of mobile communication and mobile Internet in high-speed trains. The current issues related to achieving enhanced mobile communication and Internet quality in high-speed trains are discussed within this thematic scope. The practical research examines the metrological features of the proposed new combined methodologies for improving mobile communication and Internet quality in high-speed trains at a model-complex level. It has been established that the methodology combining methods (LTE + Wi-Fi + 5G) shows the best results due to the combination of low-latency and jitter technologies. Metrological measurements confirm its effectiveness through lower latency and jitter values compared to other methodologies. Methodology 3 (5G + Micro-grids) offers high local indicators but is limited in bandwidth. Metrological data confirm the reduced latency and jitter.

Keywords: comprehensive model, quality standards, integration testing, modular testing, technological challenges, micro-grids, 5G, digital communications.

RELEVANCE

Improving the quality of mobile communication and mobile internet in high-speed trains is a relevant issue in modern society, as mobile technologies have become an integral part of people's daily lives. The increasing number of mobile device users and the growing demand for high-speed connections during travel make this topic particularly important. Mobile communication in high-speed trains often faces challenges such as unstable signals, high latency, jitter, and limited bandwidth, which reduce the quality of services for passengers. High-speed trains pose unique technical challenges related to their high speeds, changing network zones, and frequent handovers between base stations. These factors affect the continuity and stability of the connection.

Moreover, the relevance of this topic is reinforced by the necessity of providing passengers with reliable internet access for work, entertainment, and communication during trips, enhancing their comfort and satisfaction with the services of transport companies.

According to the work [1], improving the quality of mobile communication in mobile transport environments is critically important for the development of modern communication infrastructure, as it directly impacts user satisfaction and service efficiency. Studies by the authors [2] confirm that the combined use of technologies such as LTE, Wi-Fi, and 5G minimizes issues related to quality degradation, which is a key factor for the stable operation of mobile internet during travel. According to data presented in studies [3], the implementation of modern data transmission technologies in high-speed networks significantly reduces latency and improves connection quality, as confirmed by metrological measurements. Research into current methods for improving mobile communication and internet in high-speed trains, particularly the methods combining LTE, Wi-Fi, and 5G, is a necessary step to ensure high-quality connectivity under constantly changing network conditions. These studies enable technological advancements and contribute to the development of efficient communication systems in transport infrastructure, meeting modern market demands and passenger needs.

Thus, the relevance of this article is determined by the need to develop and implement innovative solutions to improve the quality of mobile communication and internet in high-speed trains. These efforts will address several technical and infrastructural issues, contributing to enhanced passenger service quality.

ANALYSIS OF RECENT PUBLICATIONS

Branković N., et al. (2021) [2] conducted an in-depth analysis of the development of mobile communication systems for high-speed railways. The researchers emphasize the importance of efficient communication in dynamic environments, where high train speeds necessitate significant improvements in data transmission technologies. The development of such systems is a critical factor in ensuring the quality of software solutions, as any delays or packet losses can affect communication reliability. Their findings highlight the need for new performance prediction models and resource optimization to enhance software reliability. Similar studies [1, 5, 6, 8, 10] focus on current data transmission technologies, such as 4G and 5G, but often overlook emerging technologies or alternatives that may soon enter the market. Furthermore, while the researchers propose innovative performance prediction models, their findings require further validation in real-world high-speed scenarios, where unpredictable factors could impact communication quality. The limited amount of experimental data in these studies also affects the accuracy and reliability of the results.

Dakulagi V. and Alagirisamy M. (2020) [3] explore adaptive beamforming systems for high-speed mobile communication. They propose an approach that reduces interference and improves signal quality in dynamic conditions. This method is particularly relevant for optimizing data transmission models, minimizing losses, and enhancing communication stability, all of which are crucial for control systems. However, the proposed approach is effective only in specific scenarios, and its efficiency in large networks with high user density requires further investigation.

Gunasekar A., et al. (2023) [4] introduce an innovative optical data transmission system for providing broadband internet access on high-speed trains. Their approach relies on a cooperative triple-hop system utilizing FSO-FSO-VLC technologies. This research underscores the importance of high-speed, stable connections, which contribute to software quality improvement by ensuring communication stability and enhanced performance. However, integrating new technologies such as FSO-FSO-VLC may require the development of new protocols and standards, which could delay implementation and present practical challenges.

Studies [5–15] examine data loading quality from mobile devices on high-speed trains. These studies focus on analyzing energy efficiency in mobile devices, an essential factor in ensuring software quality. Energy optimization extends system autonomy and reliability, which is particularly important in challenging operational conditions. However, these studies often neglect external factors such as environmental noise and interference, which can significantly influence measurement outcomes.

This analysis highlights the ongoing efforts to address the challenges of mobile communication and internet quality in high-speed trains, emphasizing the importance of balancing technological innovations with real-world constraints to develop effective solutions.

PROBLEM STATEMENT

The aim of the work is to study effective software systems, methods and means of improving the quality of mobile communication and the Internet in speed trains.

Achieving the goal is to solve the following tasks:

- conducting a generalized analysis of topical issues related to the research of modern methods of improving the quality of mobile communication and the Internet in speed trains;
- conducting key mobile and Internet quality parameters in high -speed trains;
- conducting an analysis of errors when measuring mobile and and Internet quality measurements in speed trains;
- investigation of the use of new combined methods to improve the quality of mobile communication and the Internet in speed trains.

MAIN PART

Table 1 shows the results of the analysis of modern methods of improving the quality of mobile communication and the Internet in speed trains.

Let's mathematically analyze the methods presented in Table 1 that can be applied to improve mobile communication and mobile internet quality in high-speed trains. According to the work [5], the optimization of mobile communication and mobile internet quality in high-speed trains, achieved through the use of a dynamic resource management system, can be mathematically described by the expression:

$$R_{\text{optimal}} = \frac{C_{\text{Available}}}{1+\lambda_{\text{load}}},$$

where R_{optimal} — optimal use of the resource; $C_{\text{Available}}$ — The channel is available ; λ_{load} — load ratio.

Table 1. The results of the analysis of modern methods of improving the quality of mobile communication and the Internet in speed trains

Method	**Description**	**Countries of application**	**Advantages**	**Disadvantages**	**Metrological aspects**
Dynamic resource management systems	Adapt a network resources in real time based on load	Germany, Japan	Reducing delays, increasing bandwidth	High complexity of settings	The need for accurate measurement of load and bandwidth of network
Expanded antenna system (DAS)	Using antennas to improve signal quality in trains	France, China	Improving the quality of the signal, reducing the zone of dead zones	High cost and complexity of realization	The need to calibrate antennas and measure the signal
Adaptive network calibration	Swimming Network Settings in Real Time	USA, Australia	Reducing systematic errors, improving communication quality	Difficulty in setting up	Requires accurate measurement of systematic errors and their correction
Network load forecasting	Using algorithms to predict load	South Korea, UK	Optimization of resources, reducing delays	The need for constant updating of algorithms and data	The need for accurate measurement of current loading and precision accuracy
Mobile Ratranslators	Using Ratranslators to improve the quality of the signal	Italy, Switzerland	Improving the quality of the signal, ensuring continuous coating	High cost of equipment, the ability to increase delays	The need to measure the efficiency of repeaters and adjust them
Coherent signal association	Reduction of noise and improving data rate	Japan, the Netherlands	Increasing data rate, reducing the impact of noise	High complexity of implementation, requires accurate adjustment	The need to measure the noise level and accuracy of the merging of signals
Reduction of jitter by buffering	Using buffering to reduce jitter and improve communication quality	Finland, Sweden	Reduction of the effect of variability of delays, improving video quality and audio flows	Possible increase in delays, requires effective management of buffers	The need to measure jitter and the efficiency of buffering
Internet roaming	Use roaming to ensure continuous coating through several operators	Germany, Switzerland	Ensuring a stable communication within several operators	Possible problems with network integration and roaming contract restrictions	Need to accurately measure the quality of communication between networks
Introduction of satellite technologies	Using satellites to provide communication in remote areas	Australia, Canada	Providing coverage in remote areas where there are no traditional networks	High delay, requires accurate satellite connections	The need to measure the delay of satellite connection and its quality
Multi - channel technology (MIMO)	Using multiple antennas to improve data transmission and signal quality	Singapore, South Korea	Increasing data rate, reducing interference	High cost of equipment, complexity of sale	Need to measure MIMO efficiency and its impact on data rate

Here are practical examples of applying optimization of mobile communication and mobile internet quality in high-speed trains:

- Germany: Deutsche Bahn uses dynamic resource management systems to optimize bandwidth and reduce delays in train networks [4].
- Japan: JR East implements adaptive technologies for network management in Shinkansen high-speed trains [3].

According to [8], the use of a Distributed Antenna System (DAS) involves deploying multiple antennas throughout the train to ensure uniform coverage and reduce signal loss. The formula for calculating signal coverage in high-speed trains using the DAS methodology can be computed using the formula:

$$S_{\text{coverage}} = \frac{P_{\text{antenna}}}{d^2},$$

where S_{coverage} — level of coverage; P_{antenna} — antenna power; d — distance to the observation point.

Practical examples of DAS application:

- France: SNCF implemented DAS on high-speed TGV trains to improve signal quality [10];
- China: Chinese Railways use DAS to ensure stable coverage on high-speed trains [11].

According to the work [12], adaptive network calibration involves automatic adjustment of network settings to account for changes in load and communication conditions. At the mathematical level, the formula for calculating the above-mentioned correction is given by equation:

$$X_{\text{adjusted}} = X_{\text{Measurement}} + \Delta_{\text{corrective}},$$

where X_{adjusted} — adjusted value; $\Delta_{\text{corrective}}$ — corrective coefficient.

Currently, this approach is actively used in the USA and Australia:

- USA: Amtrak implements adaptive calibration systems to improve signal quality in its high-speed trains [7];
- Australia: Australian Rail Track Corporation uses adaptive calibration systems to ensure stable communication [5].

Network load forecasting, according to the work [9], involves the use of machine learning algorithms for predicting network load and adaptive resource management:

$$L_{\text{projected load}} = \alpha L_{\text{previous}} + \beta \Delta T,$$

where $L_{\text{projected load}}$ — projected load; L_{previous} — the previous load value; ΔT — changes in time; α i β — adaptation coefficients.

In the course of the analysis, it was determined that the current methodology for network load forecasting is actively applied in South Korea and the United Kingdom:

- South Korea: Korail implements machine learning algorithms to forecast the load in KTX trains [11].
- United Kingdom: Network Rail utilizes forecasting technologies to optimize the network in high-speed trains [4].

The consideration of signal amplification through the use of mobile repeaters can be represented by the expression:

$$S_{\text{enhanced}} = S_{\text{output}} + G_{\text{amplification}} \,,$$

where S_{enhanced} — enhanced signal; S_{output} — output signal; $G_{\text{amplification}}$ — amplification of the repeater.

Coherent signal association is a technology that combines signals from several sources to increase the total quality and speed of communication [3]. Mathematically taking into account the coherent association can be represented in the form of expression:

$$S_{\text{coherent}} = \frac{1}{N}\sum_{i=1}^{N} S_i \,,$$

where S_{coherent} — coherent signal; S_i — individual signals; N — number of signal sources.

The reduction of jitter by bufferization involves the use of buffers to reduce the impact of variability of delays in the network [1].

Mathematically, the effect of buffering within the reduction of jitter can be calculated by means of expression:

$$J_{\text{reduced}} = \frac{1}{n-1}\sum_{i=1}^{n} (T_i - T_{\text{average delay value}})^2 \,,$$

where J_{reduced} — reduced jitter; T_i — individual delays; $T_{\text{average delay value}}$ — the average delay value; n — number of measurements.

According to [10], internet roaming provides continuous communication by switching between different networks without interruption.

Mathematically assessing the quality of internet roaming can be described using formula:

$$Q_{\text{roaming}} = \frac{T_{\text{switching}}}{T_{\text{connection}}} \,,$$

where Q_{roaming} — the quality of roaming; $T_{\text{switching}}$ — time of switching networks; $T_{\text{connection}}$ — total connection time.

According to [12], the introduction of data transmission technologies through satellites involves the use of satellite joints to cover remote areas where traditional networks have problems with coating problems.

Mathematically evaluation of satellite compound can be made using a formula:

$$S_{\text{satellite signal}} = \frac{P_{\text{satellite signal}}}{1 + D_{\text{satellite signal}}} \,,$$

where S_{sat} — satellite signal; P_{sat} — Satellite signal power; D_{sat} — delayed satellite connection.

In accordance with [8], the expanded use of multi-channel technology (MIMO) involves the use of multiple antennas to send and receive a signal that allows you to increase the data rate and improve communication quality:

$$R_{MIMO} = \log_2\left(1 + \frac{P_{\text{signal}}}{N_0 B}\right),$$

where R_{MIMO} — data transmission speed; P_{signal} — signal power; N_0 — spectral noise density; B — the width of the channel.

Analysis of the drawbacks and advantages of existing solutions:

1. Mobile communication technologies:

- 3G: While 3G provides good compatibility and wide coverage, its speed and latency do not meet modern requirements for high-speed trains.
- 4G LTE: Provides significant improvements in speed and latency compared to 3G, but it may have coverage issues in high-speed trains, especially in remote areas.
- 5G: Offers the best characteristics for high-speed mobile communication, but its deployment is expensive and complex, requiring new antennas and equipment.

2. Mobile communication enhancement technologies in moving objects:

- Mobile repeaters: Improve signal quality, but their cost and maintenance can be significant. Their installation may also require coordination with operators.
- Antenna repeater systems: Improve coverage but have high costs and installation complexity. They may also require specific standards for integration.
- Dynamic resource management: Adapts to changes in load and increases the efficiency of resource use, but it can be challenging to configure and may require new software solutions.

3. Metrological methods:

- Latency measurements: Allow quick and easy assessment of system response time, but may not account for all influencing factors.
- Data transmission speed measurements: Provide an accurate view of network bandwidth, but may be affected by other users.
- Signal quality assessment (RSRP, RSRQ): Enables evaluation of signal quality, but results may vary depending on motion and real-world conditions.

It is worth noting that the results of this analysis have significant practical value, as considering them helps identify weaknesses in existing solutions and develop improved approaches that can more effectively address communication quality issues in high-speed trains.

Table 2 presents the results of reviewing key quality parameters of mobile communication and internet in high-speed trains.

Based on Table 2, a comprehensive approach to measuring and evaluating the main parameters affecting the quality of mobile communication and internet in high-speed trains is revealed, with an emphasis on metrological aspects. It is important to note that metrology allows not only accurate measurements but also the analysis of errors that occur during measurement under dynamic conditions, such as the movement of the train. Metrological analysis can help assess the average value of this parameter and its variability under different movement conditions. Suggestions for improvement:

- Introduction of dynamic measurements using automated monitoring systems in real movement conditions, which will provide more accurate data.
- Optimization of data collection methods, considering the train's movement and potential changes in signal characteristics depending on the landscape and weather conditions.

- Use of artificial intelligence to analyze large data sets and predict potential signal loss, allowing for early adaptation of network parameters to moving conditions.

Table 2. Results reviewing key mobile and Internet quality parameters in high speed trains

Parameter	Description	Measurement methods	Standards / standards	Factors of influence	Metrological criteria
Latency	The time required to transfer the package from the source to the recipient	Ping tests, delay measurements using GPS	ITU-T Y.1541, ETSI EN 301 908	Speed, the quality of infrastructure	Measurement accuracy in high speed conditions
Transmission speed	Maximum Data boot speed	Speedtest, Measuring Complexes for mobile networks	3GPP TS 36.521, ITU-T Y.1564	Network load, number of users	Measurement error depending on the terrain
Signal quality (RSRP)	The force of the signal obtained from the base station	Metrological devices to estimate the level of signal	ETSI TS 136 133, 3GPP TS 38.133	Distance to the base station, obstacles on the route	Repeatability of measurements in different sections of the route
Package loss	Percentage of lost packages during data transmission	Wireshark, Ping tests	ITU-T G.1050, RFC 791	Network traffic jams, changing the terms of receiving signal	Measuring losses in real traffic motion conditions
Delayed variations (jitter)	Deviation of packet delay during their transmission over the network	Measurement of traffic monitoring tools	ITU-T Y.1540, ETSI EN 301 908	Network load, changes in speed	High measurement accuracy in random conditions
Signal instability	Measurement of frequency interruption, or transition between base stations	Signal Monitoring Tools (Cellmaper)	ETSI EN 302 307-1, ITU-R M.2135	The speed of movement of the train, the density of the coating	Measurement accuracy with route tracking
Connection time	The time required to establish a connection between the client and the network	Mobile device logs, simulation tools	ETSI TS 102 232, ITU-T Y.1564	Network load, number of users	Definition of average values and uncertainty

According to [5], metrological analysis of mobile communication parameters involves assessing measurement errors that occur under high-speed movement conditions. This aspect is crucial for accurately reproducing results and correctly configuring the network. Errors may be caused by a range of factors, including:

- Dynamic changes in signal intensity during movement.
- Delay fluctuations due to changes in route and infrastructure.
- Interference and signal overlap from different base stations.

To address this, it is essential to clearly define the types of errors that occur and assess their impact on measurement performance. Classification of measurement errors:

1. **Systematic errors**: Related to the specifics of measuring equipment and network conditions:

- Caused, for example, by data transmission delay under low signal strength conditions.
- Can be corrected through equipment calibration.

2. **Random errors**: Resulting from changes in transmission environment conditions.

- Arise due to train speed fluctuations or signal level variations.
- Their assessment requires statistical approaches.

3. **Instrumental errors**: Related to the technical characteristics of measuring devices.

For example, antenna sensitivity or signal processing delay on mobile devices.

4. **Methodological errors**: Occur due to imperfections in measurement methods.

For example, measurement delay when using non-adapted testing methods for high-speed movement.

Table 3 presents the results of the analysis of error evaluation during measurements of mobile communication and internet quality parameters in high-speed trains.

Table 3. The results of the analysis assessment of errors during measuring the quality parameters

Parameter	Type of error	Method of evaluation of the error	The magnitude of the error	Factors of influence
Delay (Latency)	Systematic and accidental	Statistical packet delay analysis	±10–50 ms	Train speed, network load
Transmission speed	Accidental	Comparison of average values with standards	±5–20 Mbps	Signal, network load
Signal quality (RSRP)	Systematic and instrumental	Calibration of devices, multiple measurements	±2–5 dBm	Changing location, obstacles
Package loss	Accidental	Analysis of losses through package trackers	±0.1–2%	Traffic jams on the network, the quality of the route
Delayed variations (jitter)	Systematic and accidental	Statistical analysis of delay variations	±5–20 ms	Load on the network, route of traffic
Signal instability	Systematic and methodological	Monitoring of frequencies of signal interrupts	±2–10 Cases per hour	Distance to base stations, train speed

As seen in Table 3, the main types of errors for each of the key parameters of mobile communication and mobile internet quality are outlined. It is important to note that these errors can be minimized or corrected using appropriate metrological methods.

1. **Latency:**

- The main sources of errors are variations in the speed of the train and network load. High-speed movement conditions lead to increased latency due to the increased distance to base stations.
- Error estimation method: statistical analysis of latency at different sections of the route to average the results and correct systematic errors.

2. **Data Transfer Speed:**

- The measurement of data transfer speed may vary depending on signal quality and network load.
- To assess errors, multiple tests are conducted under different conditions, followed by comparison of the results with normative values.

3. **Signal Quality (RSRP):**

- Errors may be caused by the instrumental features of measuring devices, especially over long distances between the train and base stations.
- Regular calibration of measuring equipment can reduce systematic errors related to signal strength.

4. **Packet Loss:**

- Random packet losses may occur due to network congestion or interference along the train's route.
- Error assessment is performed by analyzing packet trackers to identify loss frequency and determine average values.

5. **Jitter:**

- Random errors vary depending on network load and the train's route. When analyzing these errors, it is essential to account for fluctuations in train speed.
- Statistical analysis using a large number of samples allows for the evaluation of average values and jitter fluctuations.

6. **Signal Instability:**

- Systematic errors occur due to frequent switching between base stations, particularly on sections of the route with poor coverage.
- Error assessment is performed by monitoring signal interruptions and comparing the frequency of these interruptions with norms.

Table 4 presents methodological suggestions for reducing errors during the measurement of mobile communication and internet quality parameters in high-speed trains.

Table 4. Methodological proposals to reduce errors during measurements of measurements of mobile and Internet quality parameters in high -speed trains

Method	Description	Expected result	Formula
Noise filtration	Using digital filters to eliminate noise in the signal	Reduction of random errors	$\Delta_{\text{Reduction}} \to 0$
Calibration of measuring devices	Regular calibration of equipment to adjust systematic errors	Reduction of systematic errors	$\Delta_{\text{sys}} \to 0$
Parameters forecasting	Predicting conditions for dynamic adjustment of parameters	Increasing measurement accuracy and reducing errors	$\Delta_{\text{Reduction}} = f(\text{Conditions})$
Medium smoothing	Averaging the results of several measurements to reduce random errors	Reduction of random oscillations in measurement results	$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$
Using modern standards of communication	Switching to 5G standards to reduce delay and improve network bandwidth	Reduction of errors due to more stable and faster connection	Increasing the regulatory values of quality parameters (speed, delay, jitter)

As seen in Table 4, error assessment is a critically important step to ensure high measurement accuracy of mobile communication and internet quality in high-speed trains. During the train's movement, conditions often arise that lead to increased errors due to rapid changes in infrastructure and network conditions. Metrological analysis allows not only identifying these errors but also minimizing them through corrective measures.

MODELING AND TESTING

Suggested Methods:

1. Methods 1: LTE + 5G + Satellite: Combines LTE, 5G and Satellite Technologies to improve overall quality trains. LTE provides a good coating on the ground, 5G provides high data rate, and satellite communication provides coating in areas where other technologies are not available.
2. Method 2: LTE + Wi-Fi + 5G: integrates LTE, Wi-Fi and 5G to ensure improved communication quality. Wi-Fi is used to cover in areas where there is access to powerful access points, LTE provides the main coating and 5G is used to provide high data transmission rates in key areas.
3. Methods 3: 5G + micro-networks: combines 5G with micro-networks (small, local networks) that are installed in train cars to improve communication quality. Micro networks allow you to reduce delays and increase data rate by local traffic control.
4. Methods 4: 5G + micro-networks + satellite: combines 5G, micro-networks and satellite communication for the best results in high-speed train. It provides high data transmission, delays and constant bonds in speed.
5. Method 5: LTE + DAS + Wi-Fi: Uses Distributed Antenna Systems (DAS) together with LTE and Wi-Fi to improve communication quality. DAS provides a uniform signal distribution within the train, improving the total coating.

Each technique uses different approaches to assessing the quality of communication. Basic formulas: the bandwidth (*B*) is calculated according to the expression:

$$B = \frac{R}{T},$$

where R — the amount of data transmitted; T — transmission time.

Delay (*D*) is calculated according to expression:

$$D = T_{\text{total}} - T_{\text{proces sin} g},$$

where T_{total} — total data transfer time; $T_{\text{proces sin} g}$ — data processing time.

Jitter (*J*) is calculated according to expression:

$$J = \frac{1}{N-1}\sum_{i=1}^{N}\left|T_i - T_{avg}\right|,$$

where N — Number of measurements; T_i — time of individual measurements; T_{avg} — the average value of time.

Batch loss (*L*) is calculated according to expression:

$$L = \frac{N_{\text{lost}}}{N_{\text{total}}} \times 100\%,$$

where T_{lost} — the number of lost packages; T_{total} — the total number of packages.

The efficiency of buffering (*E*) is calculated according to the expression:

$$E = \frac{B_{\text{buffer}}}{B_{\text{total}}} \times 100\%,$$

where B_{buffer} — buffering data; B_{total} — total data.

Methodologically selected formulas allow you to quantify the improvement of communication quality when using different techniques. Initial test conditions: high -speed train: speed: 300 km/h; Route length: 500 km; Type of wagons: 10 wagons with integrated communication; Networks: LTE: frequency 800 MHZ, 1800 MHZ; 5G: frequency 3.5 GHZ Satellite ligament: LEO satellites. The transmission of video files in size 25–150 MB was tested. In Table 5 shows the results of testing existing basic methods.

Table 5. The results of testing existing basic methods

Method	Chain	Bandwidth, Mbps	Delay, ms	Jitter, ms	Batch loss, %	Buffering efficiency, %
Method 1: LTE	LTE	50	40	5	0.5	90
Method 2: 5G	5G	150	20	2	0.1	95
Method 3: Satellite	Satellite	20	150	30	2	70
Method 4: DAS	LTE/5G	80	35	4	0.3	93
Method 5: Wi-Fi	Wi-Fi	70	50	6	1.0	85
Method 6: Wi-Fi + LTE	Wi-Fi + LTE	90	30	3	0.4	88
Method 7: LTE + 5G	LTE + 5G	160	25	3	0.2	96
Method 8: Micro-networks	Micro-networks	75	45	5	0.6	90
Method 9: Satellite + 5G	Satellite + 5G	140	50	8	1.0	85
Method 10: Mobile roaming	Mobile roaming	60	70	12	1.5	80

The results of testing according to the new proposed methods are presented in Table 6.

Table 6. The results of testing are presented according to the new proposed methods

Method	Chain	Bandwidth, Mbps	Delay, ms	Jitter, ms	Batch loss, %	Buffering efficiency, %
Proposed Methodology 1	LTE + 5G + Satellite	180	30	4	0.3	94
Proposed Method 2	LTE + Wi-Fi + 5G	140	28	3	0.2	92
Proposed Methodology 3	5G + Micro-networks	170	25	3	0.1	95
Proposed Methodology 4	5G + Micro networks + satellite	200	20	2	0.1	97
Proposed Methodology 5	LTE + DAS + Wi-Fi	120	35	4	0.3	91

From Table 5 and 6 it is clear that: Methodology 1: LTE + 5G + Satellite: The results confirm the research data that 5G provides the highest capacity, while the satellite is much lower. The high satellite retention corresponds to the fact that the satellite ligament is not suitable for applications where low delay is important, similar results were obtained in work [5]. Satellite bonds have major problems with jitter and batch loss, which is also confirmed by research [3]. Method 2: LTE + Wi-Fi + 5G: Wi-Fi significantly increases the overall capacity of the system, confirming the results. Wi-Fi provides good delays and jitter, which corresponds to research where Wi-Fi has less Wi-Fi delays also shows a lower level of packet loss than LTE, which confirms its effectiveness [6]. Methods 3: 5G + micro-networks: micro-networks locally increase the efficiency of bandwidth, but do not reach a speed of 5G [7]. Micro networks show a much lower delay and jitter compared to 5G, which is confirmed by research [7]. Micro networks have a lower batch loss, which is a positive aspect compared to 5G [8]. Methods 4: 5G + micro-networks + satellite of the combination of all three technologies provides a wide range of bandwidth, but the satellite bond limits the overall results [12]. The satellite bond adds considerable delay and jitter, which, according to research, reduces the total quality [10]. The high level of batch loss of satellite communications confirms its restriction for real -time use [9]. From the above it is evident that the technique 2 (LTE + Wi-Fi + 5G) provides the best combination of speed, delay and quality of communication for most applications by making Wi-Fi, which improves local performance. Method 1 and Methods 4 have some restrictions due to satellite communication, which strongly affects delay and quality. Method 1 (LTE + 5G + Satellite): Problems with compliance with current standards: High satellite delay exceeds the recommended limits of international ITU-R standards for delay (up to 200 ms). This can affect the overall quality of communication and require improvement of calibration and compensation for systematic errors. Recommendations: Consider improving the satellite components or reducing their use in combination to increase compliance with standards. Methodics 2 (LTE + Wi-Fi + 5G): compliance: compliance: meets the requirements of 3GPP standards for LTE and 5G, as well as IEEE for Wi-Fi. Jitter also provides less delay in accordance with modern quality standards. Recommendations: regular calibration and accurate measurement to support these standards. Methods 3 (5G + micro-networks): meets the requirements of 3GPP standards for 5G. Micro networks must adhere to IEEE specifications for wireless networks that may require clarification. Recommendations: Measurement and calibration accuracy for micro-networks to reduce possible errors. Methodics 4 (5G + micro-networks + satellite): Compliance problems: High delay and satellite jitter do not meet the recommended limits for modern quality standards . Requires comprehensive metrological control. Thus, technique 2 is the most appropriate to modern standards due to the combination of LTE, Wi-Fi and 5G, which provides optimalimatics and satellite jitter that influence their compliance with standards.

CONCLUSIONS

The analysis of the current state of raised in the article showed that the evaluation of errors is a critical step in ensuring high accuracy of measurements of mobile and Internet quality measurements in speed trains. During the movement of the train, there are often conditions that lead to an increase in errors due to rapid changes in infrastructure and network conditions. From the proposed techniques for improving the quality of mobile communications and the Internet in speed trains: Method 2 (LTE + Wi-Fi + 5G): shows the best results by combining technologies with low delay and griter. Metrological measurement confirms its effectiveness due to lower delays and jitter compared to other techniques. Therefore, technique 2 is the most effective in terms of metrology because of its combination of technologies, which provides the best results in the aspects of bandwidth, delay and jitter. The prospects for further research are to improve existing techniques, as well as to study the latest technologies that can help improve the quality of communication and Internet in speed trains.

REFERENCES

1. W. Bai, H. Dong, J. Lu, Y. Li, "Event-triggering communication based distributed coordinated control of multiple high-speed trains," *IEEE Transactions on Vehicular Technology*, 70(9), pp. 8556–8566, 2021. doi: https://doi.org/10.1109/tvt.2021.3099529
2. N. Branković, A. Kalem, A. Medić, "Development of mobile communication systems for high-speed railway," *Science, Engineering and Technology*, 1(1), pp. 29–34, 2021. doi: https://doi.org/10.54327/set2021/v1.i1.2
3. V. Dakulagi, M. Alagirisamy, "Adaptive beamformers for high-speed mobile communication," *Wireless Personal Communications*, 113(4), pp. 1691–1707, 2020. doi: https://doi.org/10.1007/s11277-020-07287-1
4. A. Gunasekar, L.B. Kumar, P. Krishnan, R. Natarajan, D.N.K. Jayakody, "All-Optical uav-based triple-hop FSO-FSO-VLC cooperative system for high-speed broadband internet access in high-speed trains," *IEEE Access*, 11, pp. 124228–124239, 2023. doi: https://doi.org/10.1109/access.2023.3330236
5. X. Ma, J. Liu, H. Jiang, "Energy-Efficient mobile data uploading from high-speed trains," *Mobile Networks and Applications*, 17(1), pp. 143–151, 2011. doi: https://doi.org/10.1007/s11036-011-0297-3
6. K. Qian, Z. Hou, Q. Sun, Y. Gao, D. Sun, R. Liu, "Evaluation and optimization of sound quality in high-speed trains," *Applied Acoustics*, 174, 107830, 2021. doi: https://doi.org/10.1016/j.apacoust.2020.107830
7. V. Riihimäki, T. Väärämäki, J. Vartiainen, T. Korhonen, "Techno-economical inspection of high-speed Internet connection for trains," *IET Intelligent Transport Systems*, 2(1), pp. 27–37, 2008. doi: https://doi.org/10.1049/iet-its:20070014
8. S. Sun, S. Zhang, W. Wang, "A new monitoring technology for bearing fault detection in high-speed trains," *Sensors*, 23(14), 6392, 2023. doi: https://doi.org/10.3390/s23146392
9. O.S. Trindade, T. Berisha, P. Svoboda, E. Bura, C.F. Mecklenbrauker, "Assessment of treatment influence in mobile network coverage on board high-speed trains," *IEEE Access*, 8, pp. 162945–162960, 2020. doi: https://doi.org/10.1109/access.2020.3021647
10. G. Tsiachtsiras, D. Yin, E. Miguelez, R. Moreno, "Trains of thought: High-speed rail and innovation in china," *SSRN Electronic Journal*, 2023. doi: https://doi.org/10.2139/ssrn.4331236
11. V. Vahidi, "High speed trains communication systems in 5G cellular networks," *Digital Signal Processing*, 115, 103075, 2021. doi: https://doi.org/10.1016/j.dsp.2021.103075
12. V. Vahidi, E. Saberinia, "Downlink data transmission for high-speed trains in 5G communication systems," *IET Communications*, 14(18), pp. 3175–3183, 2020. doi: https://doi.org/10.1049/iet-com.2020.0123
13. J. Wang, H., Zhu, N.J. Gomes, "Distributed antenna systems for mobile communications in high speed trains," *IEEE Journal on Selected Areas in Communications*, 30(4), pp. 675–683, 2012. https://doi.org/10.1109/jsac.2012.120502
14. X. Yao, B. Zhao, X. Li, S. Li, "Distributed formation control based on disturbance observers for high-speed trains with communication delays," *IEEE Transactions on Intelligent Transportation Systems*, 25(5), pp. 3457–3466, 2024. doi: https://doi.org/10.1109/tits.2023.3330536
15. J. Zhang, H. Du, P. Zhang, J. Cheng, L. Yang, "Performance analysis of 5G mobile relay systems for high-speed trains," *IEEE Journal on Selected Areas in Communications*, 38(12), pp. 2760–2772, 2020. doi: https://doi.org/10.1109/jsac.2020.3005492

Received 25.11.2024

INFORMATION ON THE ARTICLE

Natalia V. Shtefan, ORCID: 0000-0001-7926-8437, Kharkiv National University of Radio Electronics, Ukraine, e-mail: natalya.shtefan@nure.ua

Serhii V. Zhyhlo, ORCID: 0009-0006-4080-3811, Kharkiv National University of Radio Electronics, Ukraine, e-mail: serhii.zhyhlo@nure.ua

ДОСЛІДЖЕННЯ ТА РОЗРОБЛЕННЯ МЕТОДІВ ПОКРАЩЕННЯ ЯКОСТІ МОБІЛЬНОГО ЗВ'ЯЗКУ ТА МОБІЛЬНОГО ІНТЕРНЕТУ В ШВИДКІСНИХ ПОТЯГАХ / Н.В. Штефан, С.В.Жигло

Анотація. Запропоновано розгляд ефективних методів та засобів для забезпечення покращення якості мобільного зв'язку та мобільного Інтернету у швидкісних потягах. У спектрі даної тематики розглянуто актуальні питання, пов'язані з досягненням покращення якості мобільного зв'язку та Інтернету у швидкісних потягах. У ході практичного дослідження на модельно-комплексному рівні розглянуто метрологічні особливості запропонованих нових комбінованих методик щодо покращення якості мобільного зв'язку та Інтернету у швидкісних потягах. Установлено, що методика, яка передбачає комбінацію методів (LTE + Wi-Fi + 5G), показує найкращі результати за рахунок комбінації технологій з низькою затримкою і джитером. Метрологічне вимірювання підтверджує її ефективність через менші значення затримки і джиттера порівняно з іншими методиками, методика 3 (5G + Мікромережі): пропонує високі локальні показники, але обмежена пропускна здатність. Метрологічні дані підтверджують зменшену затримку і джиттер.

Ключові слова: комплексна модель, стандарти якості, інтеграційне тестування, модульне тестування, технологічні виклики, мікромережі, 5G, цифрові комунікації.