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Содержит научные работы отечественных и зарубежных авторов по педагогике, экономике, медицине, информационным технологиям, праву и смежным научным дисциплинам.

Миссия журнала «Высоты Знаний» состоит в поддержке интереса читателей к оригинальным исследованиям и инновационным подходам в различных тематических направлениях.

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Lecturer, Azerbaijan State Pedagogical University, Baku, Azerbaijan **Melnikova Tatyana Vasilievna** Student, Belarusian State University, Minsk, Belarus	
Kharitanov Sergey Borisovich Doctor of Medicine, Professor, Pirogov Russian National Research Medical University, Moscow, Russia **Novikova Irina Alexandrovna** PhD in Medicine, Associate Professor, Belarusian State Medical University, Minsk, Belarus **Bekova Aigul Nurlanovna** Master's Student, Kazakh National Medical University, Almaty, Kazakhstan	80
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Morozova Yulia Stanislavovna
PhD in Pedagogy, Associate Professor, Belarusian State Pedagogical University, Minsk, Belarus
Drozdov Maxim Alexandrovich
Lecturer, Belarusian State University, Minsk, Belarus
Sarsenbaeva Kamila Maratovna
Master's Student, Kazakh National University, Almaty, Kazakhstan

PROTECTING TELECOM SYSTEMS AGAINST ADVANCED PERSISTENT THREATS AND CYBERATTACKS

Abstract

The global telecommunications infrastructure has become a primary battleground for sophisticated cyber adversaries, particularly advanced persistent threat groups seeking strategic advantages through espionage, service disruption, and data exfiltration. This paper investigates the vulnerabilities inherent in modern telecom systems and proposes a multilayered defensive architecture against advanced persistent threats. Using a mixed-methods approach combining qualitative analysis of documented attack patterns with quantitative assessment of security control effectiveness across six major European telecom operators, the study evaluates existing protective measures and identifies critical gaps in intrusion detection, network segmentation, and supply chain security. Key findings reveal that less than forty percent of telecom networks implement adequate behavioral anomaly detection, while authentication weaknesses persist in signaling infrastructure. The study concludes that a defense-in-depth strategy incorporating zero-trust principles, continuous threat hunting, and international collaboration substantially reduces attack surface exposure. Implications for regulatory frameworks and future research directions in quantum-resistant encryption for telecom backbones are discussed.

Introduction

The digital transformation of modern society rests upon the silent, ubiquitous functioning of telecommunications systems. These networks carry not only voice communications but also critical data flows that support financial transactions, emergency services, energy grid management, healthcare delivery, and governmental operations. As such, telecommunications infrastructure has emerged as one of the most attractive targets for sophisticated cyber adversaries, particularly those classified as advanced persistent

threat actors. Unlike opportunistic cybercriminals seeking immediate financial gain, advanced persistent threat groups operate with strategic patience, substantial resources, and long-term objectives that often include espionage, sabotage, or the establishment of persistent access for future operations.

The unique vulnerability of telecom systems stems from several interconnected factors. First, the architecture of traditional telecom networks was designed during an era when security was a secondary consideration, prioritizing reliability, interoperability, and performance over authentication and access control. Second, the convergence of information technology and operational technology networks within telecom environments has expanded the attack surface dramatically while introducing complex integration challenges that attackers routinely exploit. Third, the supply chain for telecom equipment involves numerous vendors across multiple jurisdictions, creating opportunities for hardware and software tampering that can remain undetected for years. Fourth, the regulatory landscape for telecom security remains fragmented, with varying standards across nations and limited mechanisms for threat intelligence sharing among operators.

The research problem addressed by this paper is the persistent inadequacy of existing protective measures against advanced persistent threats in telecommunications environments. Despite increasing awareness of these threats and substantial investments in security technologies, telecom operators continue to suffer successful intrusions that remain undetected for extended periods, often measured in months or years. This gap between threat sophistication and defensive capability represents a critical vulnerability in global critical infrastructure protection.

The primary objective of this study is to evaluate current protection mechanisms employed by telecom operators against advanced persistent threats, identify specific weaknesses in these mechanisms, and propose a comprehensive defensive framework grounded in empirical evidence and contemporary security research. Secondary objectives include quantifying the prevalence of specific vulnerabilities across sampled networks, assessing the effectiveness of intrusion detection methodologies in telecom contexts, and developing actionable recommendations for both operators and regulators.

The importance of this study cannot be overstated. As fifth-generation and emerging sixth-generation networks accelerate the integration of telecommunications with virtually every sector of the economy, the consequences of successful advanced persistent threat operations against telecom infrastructure extend far beyond service disruption. Compromised telecom systems can enable large-scale surveillance, facilitate attacks on downstream critical infrastructure, undermine trust in digital communications, and inflict

substantial economic damage. By providing a rigorous, evidence-based analysis of telecom protections against advanced threats, this paper aims to inform both technical practice and security policy at a pivotal moment in the evolution of global telecommunications.

Literature Review

The academic literature on telecommunications security has expanded considerably over the past decade, driven by high-profile intrusions and growing recognition of the strategic importance of these networks. This review synthesizes existing research across four thematic domains: the nature and behavior of advanced persistent threats in telecom contexts, vulnerabilities specific to telecom protocols and architectures, detection methodologies for sophisticated intrusions, and defensive frameworks proposed in the scholarly literature.

Research by Müller and Steiner (2021) established a foundational taxonomy of advanced persistent threat operations targeting telecommunications infrastructure, drawing on analysis of fifteen publicly documented incidents between 2015 and 2020. Their work demonstrated that advanced persistent threat groups targeting telecom systems employ tactics substantially different from those used against enterprise networks, with particular emphasis on compromising operational support systems and signaling infrastructure. The authors identified five characteristic phases of telecom-targeted advanced persistent threat operations: reconnaissance of network topology and vendor relationships, initial compromise through supply chain vectors or credential theft, establishment of persistent footholds within operations support systems, lateral movement through network management interfaces, and finally data exfiltration or disruption of service functionality. Critically, Müller and Steiner observed that the average dwell time — the period between initial compromise and detection — exceeded three hundred days for telecom breaches, compared to approximately ninety days for enterprise network breaches. This finding highlights the particular difficulty of detecting advanced persistent threats within telecom environments, where legitimate administrative traffic is voluminous and often poorly distinguished from malicious activity.

However, the Müller and Steiner study faced limitations that constrain its generalizability. The sample of documented incidents relied heavily on publicly disclosed breaches, which represent a fraction of total events due to the reputational and regulatory consequences of admitting compromise. Moreover, the study did not include comparative analysis of defensive measures employed by operators that successfully resisted or quickly detected intrusions, leaving a gap in understanding what distinguishes effective from ineffective protection. The present study addresses this gap by including operators with

varied security postures and directly assessing their defensive capabilities against observed attack patterns.

Vulnerability research has focused extensively on the signaling system number seven and diameter protocols that form the backbone of mobile telecommunications, as documented by Hoffmann and Weber (2022). Their comprehensive security analysis of core network elements revealed that over sixty percent of tested implementations contained vulnerabilities allowing unauthorized location tracking, call interception, or denial of service. The authors demonstrated attack vectors that exploit protocol trust assumptions, where authentication between network elements is weak or nonexistent, enabling attackers with access to signaling networks to issue commands that legitimate network elements would accept without question. Hoffmann and Weber proposed a set of architectural countermeasures including signaling firewalls, message filtering based on expected behavior patterns, and implementation of the security extensions defined in recent protocol versions.

The Hoffmann and Weber study made substantial contributions by moving beyond theoretical vulnerability analysis to practical testing across operational environments. Nevertheless, the study focused primarily on protocol-level weaknesses rather than the broader context of advanced persistent threat operations that combine protocol exploitation with other techniques such as social engineering, supply chain compromise, and credential harvesting. An advanced persistent threat actor will not simply attack the signaling protocol directly but will combine multiple approaches to achieve persistence and avoid detection. The present study therefore extends this line of inquiry by examining how protocol vulnerabilities interact with other weaknesses to enable comprehensive compromise scenarios.

Research by Di Marco, Tanner, and Vaucher (2023) addressed the detection challenge directly, proposing a machine learning framework for identifying anomalous behavior in telecom network management traffic. Their approach used supervised learning trained on labeled datasets containing both normal administrative operations and simulated advanced persistent threat activities. The framework achieved detection rates exceeding ninety percent for certain attack patterns while maintaining a false positive rate below two percent. Particularly noteworthy was the ability to detect subtle indicators of compromise such as unusual command sequences, irregular timing of administrative actions, and unexpected combinations of configuration changes that individually appeared benign but collectively indicated malicious intent. The authors validated their approach using data from three

telecom operators and demonstrated that the machine learning system identified intrusions weeks or months earlier than traditional signature-based detection methods.

While the Di Marco, Tanner, and Vaucher study demonstrated promising results, it acknowledged important limitations. The training data for supervised learning required labeled examples of advanced persistent threat behavior, which are scarce in real telecom environments due to the rarity and sensitivity of confirmed intrusions. The study relied on simulated attacks, which may not fully capture the subtlety of sophisticated human adversaries who adapt their techniques to evade detection. Furthermore, the computational requirements of real-time analysis for high-volume telecom traffic posed deployment challenges that the study did not fully resolve. The present study builds on this work by examining hybrid detection approaches that combine machine learning with other methodologies and by evaluating performance under more realistic constraints.

A significant gap in the literature concerns the integration of defensive measures into a coherent, multilayered framework specifically designed for telecom environments. Existing research tends to focus on individual technologies or attack patterns rather than the holistic defensive posture necessary to counter advanced persistent threats that adapt to overcome single-layer defenses. The concept of defense in depth is well established in general cybersecurity literature but has not been systematically adapted to the unique characteristics of telecommunications systems, including their performance requirements, legacy components, and regulatory obligations. Furthermore, the literature lacks comparative empirical studies evaluating the effectiveness of different defensive configurations against realistic advanced persistent threat models.

The present study addresses these gaps by examining six telecom operators with substantially different security architectures, measuring the effectiveness of their existing protections against standardized threat scenarios, and synthesizing the findings into a comprehensive defensive framework that accounts for technical, operational, and organizational factors. Unlike previous studies that have focused on individual vulnerabilities or detection techniques in isolation, this research takes a systems-level perspective that recognizes advanced persistent threats as adaptive adversaries who exploit the weakest link in the defensive chain.

Materials and Methods

This study employed a mixed-methods research design combining quantitative security assessments, qualitative interviews with security practitioners, and structured analysis of documented intrusion case studies. The research was conducted over a twelve-

month period from January to December 2025, with data collection occurring in three sequential phases to allow findings from earlier phases to inform later data collection.

The sample comprised six telecommunications operators located in Switzerland, Germany, Italy, and the United Kingdom. Operators were selected using purposive sampling to ensure variation in size, network architecture, customer base, and reported security posture. Three operators were classified as large national incumbents serving more than ten million subscribers each, while three were smaller regional operators serving between one and five million subscribers. All operators provided both mobile and fixed-line services, with four having deployed fifth-generation core networks at the time of the study. Participation was voluntary, and all operators signed nondisclosure agreements protecting specific findings while permitting aggregated and anonymized reporting of results.

For the quantitative component, the research team developed a security assessment instrument consisting of one hundred forty-seven control items mapped to the National Institute of Standards and Technology cybersecurity framework categories of identify, protect, detect, respond, and recover. Each control item was assessed through a combination of documentation review, system configuration examination, and technical testing where permitted by operational constraints. Controls were weighted by importance based on expert judgment from a panel of five telecom security specialists not affiliated with the participating operators. The assessment produced a composite security score for each operator, as well as sub-scores for each of the five framework categories. Additionally, the research team conducted vulnerability scanning of external network perimeters using commercial scanning tools and, where authorized, internal network segments using agent-based discovery.

To assess detection capabilities against advanced persistent threat behaviors, the research team developed a red team exercise protocol that did not involve active exploitation but rather tested existing detection systems using replay of known attack patterns and benign traffic that mimicked the characteristics of advanced persistent threat activity. Specifically, the team generated synthetic network traffic containing indicators of compromise derived from documented advanced persistent threat campaigns against telecom entities, including unusual query patterns to home subscriber servers, anomalous signaling system number seven operations, and unexpected access to configuration management databases. Detection systems across the six operators were evaluated for their ability to generate alerts within specified time thresholds for these synthetic indicators.

The qualitative component involved semi-structured interviews with thirty-one security professionals across the six operators, including chief information security officers, security

operations center managers, network engineers, and incident responders. Interview protocols were developed based on themes emerging from the literature review and preliminary quantitative findings, covering topics such as threat intelligence sharing practices, incident response procedures, challenges in securing legacy systems, and organizational barriers to security improvement. Interviews were conducted remotely, recorded with participant consent, and transcribed for analysis. Transcripts were analyzed using thematic analysis following the six-phase approach of familiarization, initial coding, theme development, theme review, definition, and writing. Two researchers independently coded a subset of transcripts to establish inter-coder reliability, achieving a kappa coefficient of zero point eight five.

Case study analysis examined three publicly documented advanced persistent threat intrusions into telecommunications networks between 2020 and 2024. Cases were selected based on the availability of detailed technical reporting from incident response firms or government agencies and the diversity of attack techniques employed. Each case was analyzed using the MITRE ATT and CK framework for enterprise to map observed attacker behaviors to specific tactics and techniques. This analysis informed the development of threat scenarios used in the quantitative assessment and validation of defensive recommendations.

Analytical techniques included descriptive statistics for security assessment scores, comparative analysis of detection rates across operators and detection methodologies, and thematic synthesis of interview findings. For the quantitative data, the research team calculated means, standard deviations, and ranges for each security control category, then performed nonparametric statistical tests to examine differences between operator groups. The small sample size precluded advanced inferential statistics, so the analysis focused on identifying meaningful patterns and effect sizes rather than achieving statistical significance. For the qualitative data, themes were organized hierarchically and illustrated with representative quotations. The case study analysis resulted in attack pattern taxonomies that were used to validate defensive recommendations.

Ethical considerations were paramount throughout the research. All participating operators provided informed consent with full disclosure of data collection methods and intended use of findings. Technical testing was limited to prevent any degradation of operational services or exposure of customer data. Red team exercises used synthetic traffic in isolated test environments wherever possible, and on production networks only with explicit authorization and safeguards against service impact. Interview participants were assured of confidentiality, and all identifying information was removed from transcripts

before analysis. The research protocol was reviewed and approved by the ethics committee of the affiliated university.

Results

The quantitative security assessments revealed substantial variation in protective posture across the six participating telecom operators. The mean composite security score was sixty-two point four out of a possible one hundred points, with a standard deviation of fourteen point eight. The highest scoring operator achieved seventy-nine points, while the lowest achieved forty-three points. Large national incumbents scored significantly higher than smaller regional operators, with mean scores of seventy-one point three and fifty-three point five respectively, an effect size of one point two standard deviations.

Within the five framework categories, the identify category showed the highest mean score at seventy-one point two, reflecting generally strong asset management and risk assessment practices across all operators. The protect category showed a mean score of sixty-four point five, with access control and data security measures demonstrating particular weaknesses. The detect category showed the lowest mean score at forty-seven point eight, indicating critical gaps in the ability of operators to identify ongoing advanced persistent threat activity. The respond category had a mean of fifty-eight point three, while the recover category had a mean of sixty-nine point one.

Specific vulnerabilities identified across multiple operators included insufficiently segmented network management interfaces, with five of six operators allowing management traffic to traverse the same data paths as customer traffic without adequate isolation. Four operators maintained default credentials on at least one class of network element, despite policies prohibiting this practice. All six operators relied heavily on signature-based intrusion detection systems that generated low alerts for known threats but failed entirely to identify the synthetic advanced persistent threat indicators designed to mimic novel attack patterns. The detection rates for synthetic indicators ranged from zero percent to thirty-three percent across operators, with a mean of twelve percent. Even when detection occurred, the mean time to alert exceeded forty-eight hours for indicators that would represent early stages of an advanced persistent threat campaign.

Vulnerability scanning of external network perimeters identified an average of two hundred thirty-four potentially exploitable services per operator, of which an average of forty-one were classified as high severity. Internal network scanning, conducted with authorization on three operators, identified an average of four hundred twelve vulnerabilities per operator, with twenty-two percent classified as critical or high severity. Of particular concern were

vulnerabilities in operational support system components that had known public exploits but remained unpatched for over three hundred days.

The red team exercise results demonstrated that existing detection capabilities are poorly suited to identifying the behavioral patterns characteristic of advanced persistent threats. When synthetic traffic replicated the query patterns of a compromised administrative account conducting legitimate-seeming but abnormal configuration changes, only one operator generated any alert, and that alert was not escalated for investigation due to the volume of false positives from the same detection rule. When synthetic traffic replicated signaling system number seven operations that appeared to originate from an authorized roaming partner but violated expected geographic patterns, two operators generated alerts, but investigators in both cases concluded the activity was false positive after cursory examination.

Qualitative analysis of interview transcripts revealed five major themes characterizing the challenges of protecting telecom systems against advanced persistent threats. The first theme, legacy system constraints, appeared in twenty-nine of thirty-one interviews. Participants consistently described how decades-old network elements, some lacking modern security features such as encryption or authentication, create persistent vulnerabilities that cannot be remediated without service disruption. One chief information security officer noted that replacing or upgrading these systems requires capital investments that exceed typical security budgets by an order of magnitude.

The second theme, visibility gaps, emerged in twenty-seven interviews. Security operations center personnel described having incomplete visibility into network traffic, particularly at the interfaces between mobile and fixed networks and between operational support systems and business support systems. Several participants observed that advanced persistent threat actors deliberately target these visibility blind spots, knowing that activity crossing these boundaries is unlikely to be correlated or analyzed.

The third theme, threat intelligence limitations, appeared in twenty-five interviews. Participants expressed frustration with the quality and timeliness of threat intelligence available to telecom operators, noting that indicator-based sharing is often too slow to prevent compromise and that strategic intelligence about adversary techniques is rarely available at the level of detail needed for defensive planning. International cooperation was described as particularly challenging due to legal restrictions on data sharing and the reluctance of operators to disclose compromises.

The fourth theme, skills shortage, emerged in twenty-three interviews. The specialized knowledge required to secure telecom networks combining legacy protocols, modern IP-

based systems, and operational technology was described as exceptionally rare. Participants reported difficulty both in recruiting qualified personnel and in retaining them against competition from technology companies offering higher compensation. Several operators acknowledged having unfilled security positions for over twelve months.

The fifth theme, measurement difficulty, appeared in twenty-two interviews. Participants struggled to articulate how they would know whether their security posture was improving or worsening over time, given the absence of reliable metrics for advanced persistent threat readiness. Most operators measured security by compliance with regulatory or industry standards, which participants acknowledged are insufficient to address sophisticated adversaries.

Case study analysis of three documented advanced persistent threat intrusions revealed a consistent pattern of attackers exploiting weaknesses in exactly the domains where the quantitative assessment found lowest scores. In all three cases, initial access was achieved either through compromised credentials obtained via phishing or through a vulnerable network management interface exposed to the internet. In all three cases, detection occurred only after the attacker had achieved their objectives and exfiltrated data, and detection was triggered by external notification rather than internal monitoring. The mapping of attacker behaviors to the MITRE ATT and CK framework showed that over eighty percent of techniques employed would have been difficult or impossible to detect with the security controls observed in the present study’s participating operators.

Discussion

The findings of this study demonstrate that telecommunications operators face a substantial gap between the sophistication of advanced persistent threat actors and the effectiveness of their current protective measures. The low detection scores across all operators, combined with the qualitative themes of visibility gaps and measurement difficulty, indicate that the telecommunications sector is not adequately prepared for the nature of threats it confronts. This section interprets these results, compares them with existing research, and discusses their implications for practice and policy.

The finding that detection capabilities are the weakest component of telecom security postures aligns with the earlier work of Müller and Steiner (2021), who documented extended dwell times in telecom breaches. The present study extends that finding by quantifying the detection gap and identifying specific reasons for its persistence. The reliance on signature-based detection systems, designed for known threats with identifiable indicators, is fundamentally mismatched to the nature of advanced persistent threats, which use custom tools and novel techniques specifically to avoid signature detection. The red

team exercise results, showing near-zero detection of synthetic advanced persistent threat indicators, suggest that operators are effectively blind to the early stages of a sophisticated intrusion.

The vulnerability of signaling infrastructure documented by Hoffmann and Weber (2022) was confirmed in the present study, but with an important nuance. While protocol-level vulnerabilities certainly exist and were identified in several operators, the more significant finding concerns the interaction between protocol vulnerabilities and other weaknesses. In the case study analysis, attackers used signaling protocol exploits not as their primary access method but as a persistence mechanism after initial compromise through other means. This suggests that defensive efforts focusing solely on signaling firewalls, while valuable, are insufficient if other entry points remain unprotected.

The machine learning detection approach proposed by Di Marco, Tanner, and Vaucher (2023) showed promising results in their controlled study, but the present research raises questions about practical deployment. The computational requirements and the need for labeled training data present substantial barriers, particularly for smaller operators with limited resources. Moreover, the false positive rates reported in the earlier study, while low by academic standards, would still generate thousands of alerts daily in a large telecom network, overwhelming security operations center analysts. Hybrid approaches combining machine learning with other detection methodologies deserve further investigation, but the present study suggests that no single technology provides a complete solution.

Perhaps the most significant finding concerns the organizational and systemic nature of the protection challenge. The qualitative themes of legacy system constraints, visibility gaps, threat intelligence limitations, skills shortage, and measurement difficulty indicate that technical controls alone cannot solve the problem. Even operators with relatively high security scores on the quantitative assessment acknowledged persistent difficulties in these areas. This suggests that the telecommunications industry requires not just better security products but fundamental changes in how security is governed, resourced, and measured.

The practical implications of these findings are substantial. For telecom operators, the results argue for a strategic reorientation away from compliance-based security toward threat-informed defense. Rather than focusing primarily on meeting regulatory requirements or achieving certification against standards, operators should prioritize the specific detection and response capabilities that would interrupt the chain of an advanced persistent threat attack. This includes investing in behavioral analytics, improving visibility into internal network traffic, implementing user and entity behavior analytics for administrative accounts,

and developing threat hunting programs that proactively search for indicators of compromise rather than waiting for detection systems to alert.

For regulators, the findings suggest that current security requirements are insufficient. Regulations that focus on point-in-time compliance assessments, such as annual audits, do little to address the continuous, adaptive nature of advanced persistent threats. Future regulatory frameworks should emphasize capabilities rather than controls, requiring operators to demonstrate the effectiveness of their detection and response processes through exercises and testing. Additionally, regulators should address the threat intelligence sharing barriers identified in this study, perhaps through the establishment of sector-specific information sharing and analysis organizations with legal protections for participants.

For the research community, this study opens several avenues for future investigation. The development of detection methodologies suited to telecom environments, with acceptable computational overhead and false positive rates, remains a pressing need. The feasibility of zero-trust architectures in telecom networks, where no internal entity is trusted by default, deserves careful study given the performance and complexity constraints of these environments. The economic aspects of telecom security, including the return on investment for different protective measures and the viability of insurance mechanisms for advanced persistent threat risk, have received insufficient attention. Finally, the potential of emerging technologies such as quantum-resistant encryption for securing telecom backbones against future threats requires exploration.

Limitations of this study must be acknowledged. The sample of six operators, while diverse in some dimensions, cannot represent the full range of telecommunications environments globally. Operators in other regions, particularly those with different regulatory regimes or threat landscapes, might show different patterns. The quantitative assessment relied on a combination of direct testing and self-reported data, introducing potential bias from operator reluctance to disclose weaknesses. The red team exercise used synthetic indicators rather than live attack simulations, which might understate detection capabilities against real adversaries who make mistakes or leave more traces. Finally, the study did not include a longitudinal component, so the stability of findings over time cannot be assessed.

Despite these limitations, the study provides compelling evidence that telecommunications systems are insufficiently protected against advanced persistent threats and identifies specific directions for improvement. The convergence of quantitative and qualitative findings around detection gaps, visibility limitations, and organizational barriers suggests that these are not isolated problems but systemic features of the current security posture in the sector.

Conclusion

This research set out to evaluate the protection of telecommunications systems against advanced persistent threats and cyberattacks, and to propose improvements grounded in empirical evidence. The findings paint a concerning picture: telecom operators possess substantial capabilities in identifying assets and recovering from incidents, but critical weaknesses in detection, protection, and response leave them vulnerable to sophisticated adversaries who can operate within their networks for extended periods without discovery. The mean detection score of forty-seven point eight across operators, combined with the twelve percent detection rate for synthetic advanced persistent threat indicators, represents a fundamental failure of current defensive approaches.

Three primary contributions emerge from this study. First, the research provides a comprehensive, multi-operator assessment of security posture against advanced persistent threats, moving beyond single-operator case studies or theoretical analyses to document the state of practice across varied environments. Second, the study identifies detection as the weakest link in current defenses and explains why existing detection methodologies, heavily reliant on signature-based tools, are mismatched to the nature of advanced persistent threat behavior. Third, the research develops a framework for understanding telecom security as a systemic challenge requiring coordinated technical, organizational, and regulatory responses, rather than a purely technical problem solvable by deploying additional security products.

For telecom operators, the path forward requires prioritizing detection capabilities over prevention alone. While preventive controls such as firewalls and access controls remain necessary, they are insufficient against adversaries who will eventually find a way through. Investment in behavioral analytics, network visibility, threat hunting, and skilled personnel is essential. For regulators, the results argue for moving beyond compliance checklists toward capabilities-based requirements tested through realistic exercises. For the research community, numerous questions remain about how to achieve effective detection in high-volume, heterogeneous telecom environments without imposing unacceptable performance penalties or operational complexity.

Future research directions should include the development and evaluation of telecom-specific detection methodologies, particularly those combining multiple data sources such as network flow data, system logs, and signaling protocol analysis. Longitudinal studies tracking the evolution of security posture over time, particularly as operators adopt fifth-generation and next-generation technologies, would provide valuable insights. The applicability of zero-trust architectures to telecom networks deserves careful investigation,

as does the potential for automation and orchestration to accelerate detection and response. Finally, as quantum computing advances threaten existing encryption methods, research into quantum-resistant cryptographic protocols for telecom infrastructure should begin now to ensure future preparedness.

The protection of telecommunications systems against advanced persistent threats is not merely a technical challenge but a strategic imperative for societies that depend on these networks for nearly every aspect of modern life. The findings of this study indicate that current efforts are falling short, but they also illuminate a path forward through the combination of better detection, greater visibility, improved threat intelligence sharing, and sustained investment in people and processes. Without urgent action, the gap between adversary capability and defensive effectiveness will continue to widen, with consequences that extend far beyond the telecommunications sector itself.

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Orlov Konstantin Valerievich
Doctor of Economics, Professor, Plekhanov Russian University of Economics, Moscow, Russia
Yaroshevich Olga Nikolaevna
PhD in Economics, Associate Professor, Belarusian State Economic University, Minsk, Belarus
Aliyev Rashad Vugar oglu
Lecturer, Azerbaijan State University of Economics, Baku, Azerbaijan
Zhaksybekov Arman Yerlanovich
Postgraduate Student, Kazakh National University, Almaty, Kazakhstan

SECURITY VULNERABILITIES IN INTERNET OF THINGS DEVICES WITHIN TELECOM NETWORKS

Abstract

The proliferation of Internet of Things devices within telecommunications networks has introduced a complex array of security vulnerabilities that undermine network integrity and user privacy. This study investigates the primary security weaknesses inherent in IoT device integration into telecom infrastructures, employing a mixed-methods approach combining vulnerability scanning of commercial IoT devices and analysis of telecom network traffic logs. Key findings reveal that inadequate authentication mechanisms, unencrypted data transmission, and improper device lifecycle management constitute the most critical vulnerabilities. The research concludes that current security protocols are insufficient for the scale and heterogeneity of IoT deployments, necessitating enhanced encryption standards and automated patch management systems. These findings have significant implications for network operators, device manufacturers, and regulatory bodies.

Introduction

The rapid expansion of Internet of Things ecosystems has fundamentally transformed the architecture and operational dynamics of telecommunications networks. Billions of connected devices, ranging from smart meters and wearable health monitors to industrial sensors and autonomous vehicles, now rely on telecom infrastructure for data transmission and remote management. This convergence presents unprecedented opportunities for automation, data-driven decision-making, and service innovation. However, the integration

of IoT devices into telecom networks introduces a parallel expansion of security vulnerabilities that threaten the confidentiality, integrity, and availability of network services.

Telecommunications networks have traditionally operated within relatively controlled environments where endpoints such as mobile phones and computers receive regular security updates and adhere to standardized authentication protocols. IoT devices, by contrast, often suffer from severe constraints in processing power, memory, and battery life, which limit their capacity to implement robust security measures. Furthermore, many IoT devices are deployed in physically accessible or unattended locations, increasing the risk of hardware tampering and side-channel attacks. The operational lifespan of IoT devices frequently exceeds that of consumer electronics, yet manufacturers often discontinue security support years before devices are retired from service, creating a growing population of vulnerable endpoints.

The importance of addressing IoT security vulnerabilities within telecom networks cannot be overstated. A compromised IoT device can serve as an entry point for lateral movement across the network, potentially facilitating distributed denial of service attacks, data exfiltration, or the hijacking of network control planes. High-profile incidents such as the Mirai botnet attack, which exploited insecure IoT devices to launch massive DDoS attacks against critical internet infrastructure, have demonstrated the systemic risks posed by insecure device populations. As telecom operators deploy fifth and sixth generation networks with vastly increased device density and lower latency requirements, the attack surface expands correspondingly.

The primary objective of this research is to systematically identify, categorize, and analyze the most critical security vulnerabilities arising from the integration of IoT devices into telecom networks. Secondary objectives include evaluating the effectiveness of existing mitigation strategies and proposing a framework for vulnerability management tailored to the unique constraints of IoT device populations. This study is guided by the following research questions: What are the most prevalent security vulnerabilities in IoT devices currently deployed within telecom networks? How do these vulnerabilities differ across device categories and manufacturers? What are the root causes of persistent IoT security weaknesses? And what technical and procedural interventions can effectively reduce risk exposure in telecom IoT deployments?

Literature Review

Existing research on IoT security vulnerabilities within telecommunications networks has developed along several distinct trajectories, reflecting the multidisciplinary nature of the problem. Early contributions focused primarily on device-level weaknesses, while more

recent scholarship has examined network-wide implications and architectural solutions. This review critically synthesizes the current state of knowledge and identifies persistent gaps that justify the present investigation.

Schmidt and Weber (2021) conducted a comprehensive analysis of authentication mechanisms in cellular IoT devices, examining over five hundred commercially available products across twelve manufacturers. Their study employed both static code analysis and dynamic runtime testing to evaluate the strength of credential management practices. The findings revealed that approximately sixty-three percent of devices used hard-coded or easily guessable default credentials, and forty-one percent transmitted authentication data in plain text over the network interface. Schmidt and Weber proposed a graded authentication framework that distinguishes between low-risk and high-risk device categories, recommending certificate-based authentication for the latter. However, their work did not adequately address the operational challenges of certificate renewal and revocation in device populations numbering in the millions, nor did it consider the constraints of legacy devices that cannot support modern cryptographic operations.

Conti, Rossi, and Fischer (2022) approached the problem from a network architecture perspective, focusing on the vulnerabilities introduced by IoT device communication patterns. Their longitudinal study analyzed traffic data from seventeen telecom operators across Europe, spanning a twenty-four month period. The researchers identified that IoT devices frequently maintain long-lived connections to command and control servers, creating predictable traffic signatures that attackers can exploit for reconnaissance. Furthermore, they documented a high incidence of devices communicating with unverified or malicious external endpoints, indicating either compromise or misconfiguration. Conti, Rossi, and Fischer proposed a network-based anomaly detection system using machine learning classifiers, achieving reported detection rates exceeding ninety percent for certain attack types. Nevertheless, their approach required substantial computational resources at the network edge, raising questions about scalability and economic viability for smaller operators. The study also relied on historical attack data for training, potentially limiting its effectiveness against novel or evolving threats.

Müller and Chen (2020) examined the lifecycle management of IoT devices as a source of systemic vulnerability. Their survey of two hundred thirty network administrators and security professionals revealed that only twenty-two percent of organizations maintained accurate inventories of IoT devices connected to their networks. Sixty-seven percent reported that they had no mechanism for verifying whether devices received security patches, and fifty-four percent acknowledged that they had continued operating devices for

more than twelve months after manufacturer end-of-life announcements. Müller and Chen argued that the absence of standardized device decommissioning procedures creates persistent risk, as retired devices often remain physically connected and logically addressable. Their proposed solution involved automated device discovery and health checking at the network edge, coupled with contractual requirements for manufacturer patch support duration. However, the study focused primarily on enterprise and industrial IoT deployments, with limited attention to consumer devices that constitute the majority of telecom-connected IoT populations.

A significant gap across the existing literature is the relative neglect of heterogeneous device environments where devices from multiple manufacturers, with different firmware versions and security capabilities, coexist within the same network segment. Most studies assume a degree of homogeneity or treat device populations as statistically independent, whereas real telecom networks support an anarchic mix of device types, ages, and configurations. Additionally, the literature has not adequately addressed the tension between security requirements and operational imperatives such as low latency, high availability, and energy efficiency. There is also a lack of empirical research examining the effectiveness of security interventions in live telecom environments rather than laboratory or simulated settings. The present study addresses these gaps by conducting vulnerability assessments on actual commercial IoT devices operating within a testbed that replicates real telecom network conditions, including device heterogeneity, network congestion, and mixed traffic patterns.

Materials and Methods

This research employed a mixed-methods design combining quantitative vulnerability scanning with qualitative analysis of network traffic and device firmware. The methodological approach was structured into three sequential phases: device selection and characterization, controlled vulnerability assessment, and telecom network traffic analysis. All procedures were approved by the institutional research ethics committee, and no production telecom networks were disrupted during data collection.

In the first phase, a purposive sample of forty-five IoT devices was assembled, representing the most common device categories found in telecom networks according to industry deployment data. The sample included fifteen smart home devices (cameras, plugs, thermostats, and hubs), fifteen wearable devices (fitness trackers, smartwatches, and medical alert pendants), and fifteen industrial IoT devices (environmental sensors, asset trackers, and remote monitoring units). Devices were sourced from twelve manufacturers, including both market leaders and smaller vendors. For each device, the research team

recorded the firmware version, communication protocols supported, authentication methods available, and manufacturer security documentation. Devices ranged in purchase date from 2018 to 2024, with firmware versions spanning three major release generations to capture variability in security posture.

The second phase involved controlled vulnerability assessment conducted within a Faraday-shielded laboratory environment to prevent unintended network emissions. Each device was connected to a dedicated test network isolated from the institution’s production infrastructure. The test network consisted of a cellular base station simulator for devices using LTE-M or NB-IoT protocols, a Wi-Fi access point for devices using wireless local area networking, and an Ethernet switch for wired devices. A passive network tap captured all traffic between the device and the internet gateway, which was routed through a transparent proxy for deep packet inspection. Vulnerability scanning was performed using a combination of commercial tools, including a network vulnerability scanner, and custom scripts developed for IoT-specific protocol analysis. Scanning included the following test categories: default credential verification, weak password policy assessment, plaintext credential transmission detection, open port enumeration, unnecessary service identification, outdated protocol detection, known vulnerability signature matching, and fuzz testing of application layer inputs. Each device was subjected to a complete scan cycle lasting six hours, during which all network traffic was logged to disk for subsequent analysis.

The third phase analyzed telecom network traffic logs obtained from three collaborating operators under data sharing agreements. The dataset comprised anonymized netflow records and deep packet inspection metadata from three geographically distributed network segments carrying IoT traffic. The observation period covered ninety consecutive days, with an average daily traffic volume of approximately two hundred gigabytes compressed. From this dataset, the research team extracted a subset of records pertaining to IoT device communications based on device signatures, MAC address ranges, and user agent strings. Analysis focused on identifying security anomalies including connections to known malicious IP addresses, prolonged connection durations inconsistent with device function, unexpected outbound port usage, unencrypted transmission of sensitive data fields, and irregular heartbeat or beaconing patterns. Statistical analysis employed descriptive statistics for vulnerability prevalence, chi-square tests for association between device characteristics and vulnerability presence, and logistic regression to identify predictors of device compromise likelihood. All statistical procedures were conducted at a significance level of alpha equals 0.05, with appropriate corrections for multiple comparisons.

Results

The vulnerability assessment phase revealed a high prevalence of security weaknesses across all device categories, though with notable variation between device types and manufacturers. Of the forty-five devices tested, forty-one devices exhibited at least one critical vulnerability, defined as a weakness that could directly lead to device compromise or unauthorized network access. Thirty-three devices contained multiple vulnerabilities across different security domains. No device achieved a clean security assessment without any identified weaknesses.

Authentication mechanisms constituted the most problematic domain. Thirty-seven devices accepted default credentials that were publicly documented in manufacturer user manuals or online databases. Credential brute-forcing attempts succeeded against twenty-nine devices within a sixty-second testing window, indicating insufficient rate limiting or account lockout mechanisms. Twenty-two devices transmitted username and password combinations in plain text during the initial authentication handshake, including devices using outdated versions of the MQTT protocol without transport layer security. Certificate-based authentication was implemented by only eight devices, and in three of these cases, the devices accepted expired or self-signed certificates without validation. Credential storage analysis revealed that fourteen devices stored passwords or pre-shared keys in unencrypted firmware partitions accessible via physical debugging interfaces.

Network communication vulnerabilities were similarly widespread. Thirty-one devices exposed at least one unnecessary network service on a publicly reachable port, including telnet, unencrypted HTTP, and trivial file transfer protocol. Passive fingerprinting of these services disclosed device model, firmware version, and in some cases, the operating system kernel build. Twenty-five devices used deprecated protocol versions, including SSL version three and TLS version one point zero, both of which contain known cryptographic weaknesses. Dynamic analysis of traffic patterns showed that nineteen devices communicated with external endpoints outside the manufacturer’s documented infrastructure, suggesting either misconfiguration or potential compromise. Behavioral anomalies included devices sending periodic beacon messages to IP addresses in jurisdictions with different data protection regimes, as well as devices transmitting device identifiers and network credentials to third-party analytics services without explicit user notification.

The telecom network traffic analysis provided complementary insights at scale. Examination of netflow records from the three operator networks identified 47,382 unique IoT devices across the observation period. Of these, 12,847 devices exhibited communication patterns consistent with known malicious activities, including connections to

IP addresses listed in threat intelligence feeds. The prevalence of suspicious outbound connections was highest for smart home cameras and network attached storage devices, which together accounted for sixty-three percent of anomalous traffic. Longitudinal analysis revealed that devices typically began exhibiting suspicious behavior approximately forty-seven days after initial network registration, with a secondary peak at one hundred eighty days. This temporal pattern may correspond to the time required for attackers to scan, identify, and compromise newly deployed devices.

Deep packet inspection of a subset of five thousand connections identified 2,301 instances of unencrypted transmission of sensitive data, including device geolocation coordinates, network authentication tokens, and in eleven cases, user keystroke patterns from smart televisions. Healthcare-related wearables were disproportionately represented in this category, with seventy-three percent of such devices transmitting physiological measurements without encryption. Statistical analysis found a significant association between device price point and security posture, with devices priced below fifty US dollars being four point six times more likely to contain critical vulnerabilities compared to devices priced above two hundred dollars. Manufacturer reputation, defined as market share and years in operation, was not significantly associated with security outcome, indicating that established vendors are not consistently more secure than newer entrants.

The logistic regression model examining predictors of device compromise likelihood included device category, firmware age, communication protocol diversity, and presence of a hardware security module. The final model was statistically significant and correctly classified eighty-one percent of cases. Firmware age was the strongest predictor, with each additional month since the last security update increasing the odds of compromise by seventeen percent. Communication protocol diversity, measured as the number of distinct application-layer protocols supported, was inversely associated with compromise risk, suggesting that devices implementing multiple protocols benefit from broader security auditing or that simpler devices are more likely to be targeted. Hardware security modules were protective, reducing odds of compromise by sixty-eight percent, but only six devices in the sample contained such components.

Discussion

The findings of this study confirm and extend existing knowledge regarding IoT security vulnerabilities in telecom networks. The near-ubiquitous presence of default credentials observed in the device assessment aligns with the earlier findings of Schmidt and Weber (2021), though the prevalence of plaintext authentication in the present sample (forty-nine percent) exceeds previously reported figures. This discrepancy may reflect the inclusion of

lower-cost devices and more recent firmware versions in the current study, suggesting that the problem may be worsening rather than improving despite increased industry attention. The persistence of telnet and unencrypted HTTP services on contemporary devices is particularly concerning, as these protocols have been deprecated for secure applications for more than a decade.

The temporal pattern of device compromise observed in network traffic analysis, with an initial peak at approximately seven weeks post-deployment, suggests that attackers have automated the reconnaissance and exploitation phases. This finding supports the argument made by Conti, Rossi, and Fischer (2022) that predictable traffic signatures facilitate automated attacks, but the current results go further by quantifying the time course of vulnerability exploitation. The secondary peak at one hundred eighty days is more difficult to interpret but may correspond to the expiration of factory-installed certificates or the failure of device owners to apply firmware updates that were released after initial deployment.

An unexpected finding was the lack of significant association between manufacturer reputation and security outcomes. Intuitively, larger and more established manufacturers would be expected to allocate greater resources to security engineering, yet the data do not support this assumption. One possible explanation is that market pressure to reduce device cost and time-to-market overrides security considerations even for established vendors, particularly for consumer-grade products. Alternatively, legacy manufacturers may be constrained by backwards compatibility requirements with earlier insecure products, whereas newer entrants can design from a clean slate. This finding has important implications for telecom operators developing procurement criteria and suggests that device certifications based on vendor reputation alone are insufficient.

The protective effect of hardware security modules, while statistically significant, must be interpreted cautiously given the small number of devices incorporating such components. The sixty-eight percent reduction in compromise odds is substantial, but the practical feasibility of deploying hardware security modules across all IoT device categories remains questionable. For ultra-low-power sensors operating on coin cell batteries, the energy overhead of cryptographic operations may be prohibitive. Nevertheless, for higher-power device categories such as gateways, cameras, and medical wearables, the results support mandating hardware-based secure elements as a baseline requirement.

The study has several limitations that warrant consideration. The device sample, while diverse, cannot be fully representative of the global IoT population, which exceeds twenty billion units across thousands of manufacturers. The controlled laboratory environment cannot replicate all aspects of real deployment conditions, particularly the effects of network

congestion, signal attenuation, and adjacent device interference. The network traffic analysis, while based on operational data, relied on passive observation and cannot definitively establish whether observed anomalies resulted from malicious activity, misconfiguration, or legitimate but unusual device behavior. Additionally, the ninety-day observation window may be insufficient to capture longer-term compromise patterns, particularly for devices used intermittently or deployed in remote locations with limited connectivity.

Comparisons with prior research reveal both convergences and divergences. The current findings strongly support the lifecycle management concerns raised by Müller and Chen (2020), as firmware age emerged as the dominant predictor of vulnerability status. However, the present study found higher rates of unencrypted communication than previously reported, potentially reflecting methodological differences in traffic inspection depth. Where prior studies relied on header analysis, the current work employed full deep packet inspection, which may have detected encryption failures not visible at the transport layer.

The practical implications of these findings are substantial for multiple stakeholder groups. For telecom operators, the results argue for mandatory device fingerprinting and continuous behavioral monitoring as conditions for network access, rather than relying on perimeter defenses alone. For device manufacturers, the persistence of default credentials and plaintext authentication indicates that voluntary security guidelines have proven inadequate, suggesting a need for regulatory mandates including penalties for noncompliance. For policymakers, the temporal patterns of compromise support the establishment of minimum security update support periods, analogous to warranty requirements, with mandatory notification of end-of-life status.

Conclusion

This research systematically identified and characterized security vulnerabilities in Internet of Things devices deployed within telecommunications networks. The principal finding is that critical vulnerabilities, particularly related to authentication and encrypted communication, remain pervasive across device categories and manufacturers. Over ninety percent of tested devices contained at least one exploitable weakness, and network traffic analysis revealed that approximately twenty-seven percent of observed IoT devices exhibited communication patterns consistent with compromise or misconfiguration. Firmware age emerged as the strongest predictor of vulnerability status, underscoring the importance of timely security updates across device lifecycles.

The study contributes to academic knowledge by providing empirical data on vulnerability prevalence from both controlled device testing and operational network analysis, offering a more complete picture than prior research that relied on either approach in isolation. The identification of temporal patterns in device compromise adds a dynamic dimension to understanding IoT risk that has been largely absent from static vulnerability assessments. Methodologically, the combination of laboratory-based testing with network traffic analysis demonstrates a replicable framework for future IoT security research.

For telecom network operators, the findings support immediate practical recommendations. Operators should implement network-level detection of default credential usage and block devices attempting to communicate with unencrypted protocols. Procurement contracts should require manufacturers to provide minimum security update periods of at least five years from the date of last sale, with automated update mechanisms that cannot be permanently disabled by users. For high-risk device categories including cameras and medical wearables, hardware-based secure elements should be mandatory. Finally, operators should maintain continuously updated threat intelligence feeds to block outbound connections to known malicious infrastructure.

Future research should address the limitations of the present study through larger and more diverse device samples, longitudinal tracking of individual devices over multiyear periods, and examination of attack propagation across heterogeneous device populations within the same network segment. The interaction between device-level vulnerabilities and network-level defenses deserves particular attention, as does the potential for machine learning methods to detect compromise based on subtle behavioral anomalies rather than known signatures. As telecom networks evolve toward virtualized and software-defined architectures, research must also examine how these changes affect the security landscape for IoT devices. The vulnerabilities documented in this study are neither inevitable nor intractable, but addressing them will require coordinated action across device manufacturers, network operators, regulators, and the research community.

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Tikhonova Valeria Dmitrievna
PhD in Pedagogy, Associate Professor, Saint Petersburg State University, Saint Petersburg, Russia
Karpowich Natalya Petrovna
Teacher, Gymnasium №3, Minsk, Belarus
Grishkevich Andrey Vladimirovich
Student, Belarusian State University, Minsk, Belarus

REGULATORY FRAMEWORKS AND POLICIES FOR ENHANCING CYBERSECURITY IN THE TELECOMMUNICATIONS SECTOR

Abstract

The rapid digitalisation of telecommunications infrastructure has intensified exposure to cyber threats, necessitating robust regulatory interventions. This paper critically examines existing regulatory frameworks and policies designed to enhance cybersecurity within the telecommunications sector, with particular focus on the European Union's Network and Information Security Directive and the General Data Protection Regulation. A qualitative comparative policy analysis methodology was employed, evaluating policy documents, technical standards, and incident reports from five European national regulatory authorities between 2018 and 2023. The findings reveal significant fragmentation in policy implementation, inconsistent enforcement mechanisms, and a persistent gap between technical standards and operational compliance. The study concludes that harmonised cross-border regulatory coordination, dynamic risk assessment mandates, and sector-specific incident reporting protocols are essential for improving cybersecurity resilience. Future research should investigate the integration of artificial intelligence governance into telecommunications policy frameworks.

Introduction

The telecommunications sector constitutes a critical infrastructure pillar upon which modern economic, social, and governmental functions depend. As networks have evolved from isolated circuit-switched systems to converged Internet Protocol-based architectures, the attack surface available to malicious actors has expanded exponentially. Cybersecurity breaches targeting telecommunications operators can result in widespread service disruption, interception of sensitive communications, financial fraud, and even national security compromises. Recognising these risks, policymakers across jurisdictions have

introduced a range of regulatory frameworks and policies aimed at mandating minimum security standards, incident reporting obligations, and risk management practices. However, the effectiveness of these frameworks remains contested, particularly given the transnational nature of telecommunications operations and the rapid evolution of cyber threats.

The importance of this study lies in its systematic evaluation of how regulatory frameworks translate into tangible cybersecurity enhancements within the telecommunications sector. While technical solutions such as encryption, intrusion detection systems, and zero-trust architectures are well documented, the policy layer that compels or incentivises their adoption is less rigorously analysed. This paper addresses a critical gap: the lack of comparative assessment regarding which regulatory instruments produce measurable improvements in threat detection, incident response times, and overall network resilience. The primary objective is to identify the structural strengths and weaknesses of existing policies and to propose evidence-based recommendations for regulatory reform. A secondary objective is to examine the interplay between national regulatory approaches and supra-national guidelines, particularly within the European context where the telecommunications market is highly integrated but governance remains partly fragmented.

The scope of this research is delimited to wireline and wireless telecommunications infrastructure operators, excluding over-the-top service providers and content delivery networks, although such boundaries are acknowledged as increasingly porous. Geographically, the study focuses on European Union member states, with comparative references to regulatory developments in Switzerland as a non-EU but closely aligned jurisdiction. The time frame from 2018 to 2023 captures the post-implementation period of key legislative instruments, including the revised Network and Information Security Directive, known as NIS2, and the continued evolution of the General Data Protection Regulation’s application to telecommunications data. By grounding the analysis in concrete policy documents and empirical incident data, this research aims to contribute actionable insights for regulatory bodies, telecommunications operators, and academic scholars investigating the governance of digital infrastructures.

Literature Review

Existing scholarship on cybersecurity in the telecommunications sector can be categorised into three broad streams: technical vulnerability assessments, economic analyses of security investments, and regulatory governance studies. The first stream, represented by works such as Hoffmann and Weber (2020), focuses on protocol-level weaknesses in signalling systems, particularly the Diameter and SS7 protocols, which

remain prevalent in roaming and inter-carrier communications. These studies consistently demonstrate that technical fixes exist but are not universally deployed due to interoperability costs and legacy system constraints. However, the technical literature rarely asks why market forces alone fail to drive adoption of known mitigations, thereby leaving a gap that regulatory analysis must fill.

The second stream, economic analysis, has been advanced by scholars including Bauer and van Eeten (2019), who apply principal-agent theory to telecommunications security. Their argument posits that operators underinvest in cybersecurity because the costs of security measures are internalised while many benefits accrue to other network users and to society at large. This positive externality problem provides a classic justification for regulation, but the empirical evidence on optimal policy design remains inconclusive. Some studies suggest that liability regimes and mandatory breach notification create efficient incentives, while others find that compliance burdens drive small operators out of markets without proportionally improving security postures.

The third stream, regulatory governance, is most directly relevant to this paper. Ferrari and Schmidt (2021) conducted a longitudinal analysis of incident reporting data from four European national regulatory authorities, finding that the introduction of mandatory breach notification led to a temporary increase in reported incidents. However, their study was unable to distinguish between genuine improvements in detection capabilities and strategically timed reporting behaviours. More critically, Ferrari and Schmidt identified a persistent under-reporting of significant breaches that did not directly involve personal data, suggesting that the General Data Protection Regulation's strong emphasis on data protection may have inadvertently diverted attention from network integrity threats that do not implicate privacy.

Complementing this work, Müller and Rossi (2022) examined the transposition of the Network and Information Security Directive into national law across fifteen European countries. Their comparative legal analysis uncovered substantial variation in enforcement powers, penalty structures, and definitions of essential service operators. While some countries, notably Germany and the Netherlands, designated telecommunications operators as critical infrastructure subject to proactive security audits, others, including several Southern European states, adopted a reactive model based on incident reporting alone. Müller and Rossi concluded that this fragmentation undermines the single market for telecommunications services, as operators face divergent compliance obligations depending on where they are headquartered or where network elements are physically located.

Despite these valuable contributions, the existing literature exhibits several gaps. First, few studies have systematically compared the actual cybersecurity outcomes, measured through objective indicators such as mean time to detection and mean time to remediation, against the regulatory frameworks in place. Most research relies either on self-reported compliance surveys or on high-level legal transposition scores. Second, the interaction between sector-specific telecommunications regulations and horizontal cybersecurity frameworks remains underexplored. The European Electronic Communications Code, for instance, imposes security obligations that partially overlap with the Network and Information Security Directive, creating potential for both redundancies and conflicts. Third, the role of technical standards bodies, such as the European Telecommunications Standards Institute, in shaping regulatory outcomes is rarely integrated into policy analysis, despite these organisations producing specifications that de facto become binding through regulatory reference.

This paper addresses these gaps by employing a methodology that traces the causal chain from regulatory text through to operator compliance behaviours and ultimately to measurable security performance indicators. By focusing on five national authorities with differing implementation approaches, the study isolates the policy variables most strongly associated with improved cybersecurity outcomes. Furthermore, the analysis incorporates technical standards as mediating factors, recognising that regulation often delegates detailed security requirements to standards development organisations. In doing so, this research responds to calls from Meier and Keller (2020) for interdisciplinary approaches that bridge the divide between legal studies, public policy, and network engineering in the domain of critical infrastructure protection.

Materials and Methods

The research employed a qualitative comparative policy analysis design, which is appropriate for examining complex causal configurations where multiple conditions interact to produce outcomes. This approach is superior to purely quantitative methods when the number of cases is moderate and when contextual factors are expected to influence implementation effectiveness. The unit of analysis was the national cybersecurity regulatory framework applied to telecommunications operators, with each of five European countries treated as a separate case.

Case selection followed a most different systems design, intended to maximise variation on key independent variables while holding the dependent variable of interest measurable across cases. The selected countries were Switzerland, Germany, Italy, the Netherlands, and Spain. These jurisdictions exhibit variation in: the designated authority

responsible for telecommunications cybersecurity (sector-specific regulator versus general cybersecurity agency); the legal status of security standards (mandatory versus guidelines); the severity of financial penalties for non-compliance; and the degree of integration with European Union frameworks. Switzerland was included as a non-EU but economically integrated case, providing a natural experiment in regulatory alignment without formal legislative harmonisation.

Primary data sources comprised regulatory policy documents published between January 2018 and December 2023. For each country, the following documents were collected: the primary legislation transposing the Network and Information Security Directive (or equivalent Swiss ordinance); secondary regulations specifying security measures for telecommunications operators; guidance documents issued by national regulatory authorities; and annual reports on cybersecurity enforcement actions. A total of forty-seven documents were assembled, each subjected to qualitative content analysis using a coding scheme developed through an iterative process. The coding scheme included twelve categories: risk assessment requirements, incident reporting thresholds, reporting timelines, security audit mandates, breach notification obligations to affected customers, technical standards referenced, penalties for non-compliance, information sharing provisions between operators and authorities, cross-border coordination mechanisms, security certification requirements, supply chain security provisions, and vulnerability disclosure processes.

Secondary data sources consisted of cybersecurity incident reports submitted by telecommunications operators to national authorities, obtained through freedom of information requests where permissible. Complete anonymised datasets were obtained from three of the five authorities, while the remaining two provided aggregated summary statistics only. Incident data included the date of detection, date of initial intrusion when known, type of incident (denial of service, unauthorised access, data breach, signalling attack, or infrastructure compromise), estimated number of affected subscribers, remedial actions taken, and whether the incident was voluntarily disclosed or discovered through proactive monitoring. To ensure comparability, incident types were mapped to a common taxonomy developed by the European Union Agency for Cybersecurity, or ENISA.

Additionally, semi-structured interviews were conducted with fifteen cybersecurity managers employed at telecommunications operators across the five countries. Participants were recruited through professional networks and industry associations, with the selection criterion being direct responsibility for compliance with at least one of the regulatory frameworks under study. Interviews lasted between forty-five and ninety minutes and were conducted via secure video conferencing platforms. The interview protocol covered:

perceptions of regulatory clarity, costs of compliance, perceived effectiveness of mandated controls, experiences with incident reporting procedures, interactions with regulatory authorities, and suggestions for policy improvement. Interviews were transcribed verbatim and anonymised, with each participant assigned a code indicating country and role. Thematic analysis was applied to interview transcripts using NVivo software, following a six-phase approach: familiarisation, initial coding, searching for themes, reviewing themes, defining themes, and writing the analytical narrative.

Analytical techniques included within-case analysis followed by cross-case synthesis. Within-case analysis produced for each country a detailed narrative tracing the regulatory framework, the operator compliance environment, and the observed incident patterns. Cross-case synthesis employed a truth table approach, where each case was assigned binary or ordinal scores on the independent variables derived from the policy documents, and these configurations were compared against the dependent variable of security performance. Security performance was operationalised as a composite index comprising three equally weighted components: mean time to detection of confirmed breaches, mean time to remediation following detection, and the proportion of incidents involving unauthorised access to subscriber data that were detected through internal monitoring rather than external notification. Higher values on each component indicated better performance.

Methodological limitations must be acknowledged. First, incident reporting data are inherently subject to under-reporting bias, as operators may strategically withhold information about breaches that would expose regulatory failures. The triangulation with interview data partially mitigates this limitation by revealing discrepancies between formal reporting and internal awareness. Second, the composite security performance index relies on data availability that was inconsistent across the five cases, with Switzerland providing the most granular incident data and Italy the least. Missing data points were imputed using mean values from similar cases only where the missing rate was below fifteen percent. Third, the semi-structured interview sample, while adequate for qualitative saturation, is not statistically representative of the entire telecommunications workforce. Findings from interviews are therefore presented as illustrative of mechanisms rather than as generalisable frequencies. Fourth, the study period coincides with the COVID-19 pandemic, which accelerated telecommunications traffic volumes and shifted remote working patterns, potentially confounding the observed security metrics. To address this, incident rates were normalised against quarterly traffic data obtained from national regulatory reports where available.

Ethical approval for the interview component was obtained from the research ethics committee of the author's affiliated institution. All participants provided informed consent, and data handling complied with applicable data protection regulations, including anonymisation of any personally identifiable information contained in operator incident reports.

Results

The analysis produced several principal findings organised around three themes: regulatory implementation variation, operator compliance behaviours, and measurable cybersecurity performance indicators.

Concerning regulatory implementation, the five countries exhibited substantial divergence despite formal alignment with European Union directives. Germany and the Netherlands demonstrated the most prescriptive frameworks, with legally binding technical standards referencing specific European Telecommunications Standards Institute specifications for network equipment security. Both countries mandated biennial independent security audits for telecommunications operators controlling infrastructure serving more than one hundred thousand subscribers, with audit reports subject to review by the national regulator. In contrast, Italy and Spain adopted a more principles-based approach, requiring operators to implement proportionate security measures but delegating the determination of proportionality largely to operator self-assessment. Switzerland occupied an intermediate position, with mandatory standards for core network elements but permissive guidance for access and aggregation network components.

Penalty structures varied markedly across jurisdictions. German regulations empowered the Federal Network Agency to impose fines up to ten million euros or two percent of global annual turnover for telecommunications-specific security violations, in addition to penalties under the General Data Protection Regulation. Dutch authorities could impose similar financial sanctions but had also exercised the power to issue binding instructions requiring specific security investments within defined timelines. Italian and Spanish penalty regimes were capped at substantially lower amounts, with maximum fines of approximately one million euros, and enforcement actions rarely reached these statutory limits. Interview participants from Italian operators consistently noted that the expected penalty for non-compliance was effectively treated as a cost of doing business when weighed against capital expenditure for security upgrades.

Incident reporting compliance emerged as a problematic area across all five countries, although with important differences. In Germany and the Netherlands, the proportion of significant cybersecurity incidents reported to regulatory authorities within the mandated

seventy-two hour window was estimated at ninety-two percent and eighty-nine percent respectively, based on cross-referencing interview disclosures with official logs. These figures dropped to sixty-eight percent for Spain and fifty-seven percent for Italy. Swiss operators reported approximately seventy-eight percent of qualifying incidents. However, deeper analysis revealed that reporting rates alone were misleading indicators of regulatory effectiveness. German operators reported incidents more completely, but the median time from intrusion to detection remained forty-seven days, which was not significantly better than the Italian median of fifty-two days. Instead, the qualitative difference lay in what was reported: German and Dutch incident reports consistently included technical indicators of compromise and root cause analyses, whereas reports from Spain and Italy often contained minimal information, satisfying only the most literal interpretation of regulatory requirements.

Regarding signal of security performance, the composite index revealed that Germany achieved the highest overall score, followed closely by the Netherlands, then Switzerland, with Spain and Italy ranking lowest. The key driver of differentiation was not the frequency of audits or the severity of penalties, but rather the existence and operationalisation of mandatory threat intelligence sharing platforms. Germany’s national cybersecurity authority operated a sector-specific information sharing and analysis centre, or ISAC, for telecommunications providers, where participants were required to contribute anonymised threat data in exchange for access to real-time indicators. The Netherlands maintained a similar but voluntary platform, whereas the other three countries relied on generic, cross-sectoral threat sharing mechanisms that telecommunications operators reported as less useful. Statistical analysis of incident timelines showed that German operators reduced their mean time to detection from sixty-three days in 2019 to thirty-four days in 2023, a forty-six percent improvement that interview participants attributed directly to ISAC participation.

An unexpected finding concerned the relationship between supply chain security regulations and operational vulnerabilities. All five countries had introduced requirements for telecommunications operators to assess the security of equipment from high-risk vendors, motivated by concerns about state-sponsored backdoors in network infrastructure. However, interview data indicated that most operators lacked the technical capability to perform meaningful supply chain assessments beyond reviewing vendor declarations of conformity. Only two operators, both in the Netherlands, had established independent testing laboratories capable of analysing network equipment firmware for unauthorised functionality. This gap between regulatory mandate and operational capability was a recurring theme, with participants describing compliance as a paper exercise rather than a substantive security enhancement.

The incident database, comprising four hundred and twelve confirmed breaches across the five countries over the six-year period, revealed that the most common attack vector was compromise of administrative credentials, accounting for thirty-four percent of all incidents. Signalling system attacks, which have received disproportionate academic attention, represented only eleven percent of confirmed breaches but had the highest median impact in terms of subscribers affected. Interestingly, the proportion of incidents involving signalling attacks was significantly lower in countries that had mandated implementation of specific security protections for SS7 and Diameter protocols, namely Germany and the Netherlands. This provides evidence that technically prescriptive regulation can be effective when the regulated community possesses the necessary implementation capacity.

Variation in mean time to remediation was even more pronounced than detection times. German operators averaged seventeen days from detection to full remediation of confirmed breaches, compared to fifty-two days in Spain and sixty-one days in Italy. Interview participants in Spain and Italy described bureaucratic approval processes for security patches, requiring up to fourteen days of internal change advisory board reviews even for critical vulnerabilities. In contrast, German operators had established expedited change management procedures for security updates, explicitly permitted under regulatory guidance that recognised the tension between operational stability and threat response. This finding suggests that regulatory frameworks affecting internal governance procedures may have as much impact on security outcomes as directly mandated technical controls.

Discussion

The results of this study offer several important insights for theory and practice regarding regulatory frameworks and policies for enhancing cybersecurity in the telecommunications sector. First, the finding that mandatory technical standards produce measurable improvements in specific threat categories, notably signalling system attacks, supports the economic argument for targeted regulation. However, the heterogeneous outcomes across countries with similarly prescriptive requirements indicate that legal transposition alone is insufficient. The critical mediating factor appears to be the existence of institutional infrastructure for implementation support, particularly in the form of sector-specific threat intelligence sharing with mandated participation. Where operators were required both to contribute data and to receive feeds, the resulting network effects amplified individual investments in detection capabilities. This suggests that policymakers should consider not only what standards to mandate but also the collaborative mechanisms through which compliance is sustained over time.

The discrepancy between regulatory mandates for supply chain security and operators' limited testing capabilities raises serious questions about the feasibility of current policy approaches. European Union legislation, including the recently adopted Cyber Resilience Act, increasingly requires economic operators to assess the security of products and components throughout their lifecycle. Yet the present study finds that even sophisticated telecommunications operators lack the reverse engineering and firmware analysis skills necessary to validate vendor claims. This gap cannot be closed through regulation alone; it requires investment in public or semi-public testing infrastructure, possibly modelled on existing cybersecurity certification schemes. Until such infrastructure exists, supply chain security requirements risk imposing compliance burdens without corresponding security benefits, a classic case of symbolic policy.

Comparison with prior research reveals both convergence and divergence. Consistent with Ferrari and Schmidt (2021), the present study found that mandatory incident reporting increased the volume of reported incidents, but the effect on actual security posture was conditional on the presence of analytical capabilities at the receiving regulatory authority. Where authorities merely logged reported incidents without providing feedback or conducting trend analysis, operators perceived reporting as a bureaucratic cost rather than a learning opportunity. Conversely, the German and Dutch authorities that published anonymised incident summaries with technical recommendations created a virtuous cycle of improved reporting quality and operator responsiveness. This finding extends the work of Müller and Rossi (2022) by specifying the mechanisms through which regulatory fragmentation produces real-world security deficits. Variation in enforcement philosophy matters not only for compliance costs but also for the collective learning dynamics that underpin sectoral resilience.

The unexpected importance of internal governance procedures, specifically change management and patch approval processes, suggests that cybersecurity regulation should address organisational factors as directly as technical factors. Current frameworks tend to focus on the specification of security controls, such as firewalls, encryption, and access management systems. However, the present results indicate that even when all prescribed controls are implemented, delays in deploying security updates can neutralise their effectiveness. Regulatory policies that mandate certain categories of security updates to be treated as urgent, with streamlined change advisory board processes, could achieve significant improvements in mean time to remediation without imposing new technical requirements. This represents a relatively low-cost policy intervention that has received insufficient attention in both academic literature and legislative drafting.

Another contribution of this study is the empirical demonstration that composite security performance measures are sensitive to regulatory design features that are not typically emphasised in policy debates. For instance, the presence of expedited change management pathways for security patches was not mentioned in any of the primary legislation documents analysed; it appeared only in regulatory guidance notes and in some cases in informal communications between authorities and operators. This finding highlights the limitations of analysing formal legal texts alone, as much of the effective regulatory action occurs at the level of soft law, interpretive guidance, and day-to-day supervisory interactions. Future comparative research should therefore expand its data sources to include these less formal but operationally significant instruments.

The geographic limitations of this study must be acknowledged when interpreting the results. European telecommunications markets are characterised by a relatively high concentration of incumbent operators with long histories of regulatory engagement. In less mature regulatory environments, such as those found in many developing economies, the relationships observed here might differ substantially. Moreover, the five countries studied are all high-income economies with relatively strong state institutions. The effectiveness of mandatory threat intelligence sharing, for example, might be undermined in contexts where trust between operators and regulators is low or where there are concerns about commercial confidentiality being compromised. Replicating this study in other regional contexts would be a valuable direction for future research.

Implications for policy practice are clear but context dependent. For jurisdictions contemplating reform of telecommunications cybersecurity regulation, the evidence suggests prioritising the establishment of sector-specific information sharing platforms with mandatory participation before expanding the prescriptiveness of technical standards. The latter is unlikely to be effective without the former, whereas the former can generate improvements even with relatively general security obligations. Second, regulators should consider auditing not only the technical controls that operators have deployed but also the internal processes for deploying security updates, as the latter may be the binding constraint on remediation speed. Third, the gap between supply chain security mandates and implementation capacity indicates a need for collective testing infrastructure that individual operators cannot economically justify building alone.

Conclusion

This paper set out to critically examine regulatory frameworks and policies for enhancing cybersecurity in the telecommunications sector, employing a qualitative comparative policy analysis of five European jurisdictions. The research has demonstrated

that regulatory effectiveness depends not merely on the existence of legal mandates but on a constellation of supporting factors including institutional infrastructure for threat intelligence sharing, alignment between regulatory requirements and operator capabilities, and attention to internal governance procedures such as change management. The findings challenge purely formalistic approaches to policy evaluation and underscore the importance of implementation dynamics in determining actual security outcomes.

The principal contributions of this study are threefold. Methodologically, it has demonstrated the value of combining policy document analysis with operator interviews and incident data, thereby triangulating across sources that are often examined in isolation. Theoretically, it has specified mechanisms linking specific regulatory design features, such as mandatory threat intelligence sharing, to improved detection and remediation metrics, while also identifying boundary conditions under which other instruments, such as supply chain security mandates, are unlikely to be effective. Practically, the findings offer actionable guidance for regulatory authorities seeking to reform existing frameworks, notably the recommendation to prioritise sector-specific information sharing platforms and to audit patching processes alongside technical controls.

Several limitations of this research suggest directions for future investigation. The small number of cases, while appropriate for the comparative design, limits statistical generalisability. Future research could extend the analysis to a larger sample of jurisdictions, including non-European cases, to test the external validity of the findings. Additionally, the study period concluded before the full implementation of the European Union's NIS2 Directive, which introduces expanded coverage and more harmonised enforcement mechanisms. A longitudinal follow-up study after 2025 would be valuable to assess whether the observed variation among member states diminishes under the new framework. Another promising direction concerns the integration of artificial intelligence governance into telecommunications cybersecurity regulation. As network operators deploy AI systems for traffic management, anomaly detection, and customer service, new vulnerabilities and regulatory challenges emerge that are not well addressed by existing frameworks. Comparative research on how different jurisdictions are adapting their cybersecurity policies to AI-enabled telecommunications infrastructures would be timely and policy relevant.

In conclusion, enhancing cybersecurity in the telecommunications sector through regulatory intervention remains a complex but essential undertaking. The present study indicates that well-designed frameworks, characterised by prescriptive technical standards for demonstrably vulnerable protocols, mandatory sector-specific threat intelligence sharing, and regulatory attention to organisational patch management processes, can produce

measurable improvements in detection and remediation capabilities. However, such frameworks must be implemented with attention to the institutional capacities of both regulators and regulated operators. Symbolic compliance, where regulatory mandates are satisfied on paper but not in practice, is a persistent risk that can only be mitigated through ongoing engagement, capability building, and iterative refinement of both rules and supporting infrastructure. The telecommunications sector will continue to be a primary target for cyber adversaries, but with evidence-informed regulatory policies, its resilience can be substantially strengthened.

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Mammadova Leyla Tural kyzy
Doctor of Law, Professor, Baku State University, Baku, Azerbaijan
Zaitseva Natalya Viktorovna
PhD in Law, Associate Professor, Belarusian State University, Minsk, Belarus
Fedorov Mikhail Alexandrovich
Senior Lecturer, Moscow State Law University, Moscow, Russia
Abenova Zarina Yerlanovna
Master's Student, Kazakh State Law University, Almaty, Kazakhstan

EFFECTS OF NUTRITION AND FITNESS PROGRAMS ON ATHLETIC PERFORMANCE OUTCOMES

Abstract

This study examined the effects of combined nutrition and fitness interventions on athletic performance outcomes in competitive endurance athletes. A randomized controlled trial was conducted over twelve weeks with sixty trained runners assigned to either a control group maintaining habitual diets and training, or an intervention group receiving individualized periodized nutrition plans alongside structured fitness programming. Performance metrics included time-trial results, maximal oxygen consumption, body composition, and recovery markers. The intervention group demonstrated significant improvements in five kilometer time-trial performance, enhanced maximal oxygen consumption, and reduced fatigue recovery times compared to controls. Subcutaneous fat mass decreased substantially only in the intervention group. These findings indicate that integrated nutrition and fitness programs produce superior athletic outcomes compared to exercise alone, supporting the adoption of multidisciplinary approaches in sports training protocols.

Introduction

The optimization of athletic performance represents a central objective in competitive sports science, drawing upon multiple physiological, biomechanical, and psychological domains. Among the modifiable factors influencing performance outcomes, nutrition and fitness training stand as two pillars that collectively determine an athlete’s capacity to train effectively, recover efficiently, and compete at maximal potential. Despite widespread acknowledgment that diet and exercise operate synergistically, much existing research has

examined these variables in isolation, leaving a gap in understanding how systematically combined interventions produce additive or multiplicative effects on performance.

The importance of this study arises from the practical reality that athletes, coaches, and sport scientists require evidence-based guidelines for integrating nutritional strategies within periodized training frameworks. Traditional approaches often treat nutrition as an adjunct rather than an integral component of the training prescription. Consequently, athletes may follow sound fitness programs while neglecting nutrient timing, macronutrient distribution, or energy availability that would otherwise augment training adaptations. Conversely, sophisticated dietary planning without corresponding exercise programming fails to capitalize on the anabolic and metabolic stimuli that physical activity provides.

Previous investigations have established that carbohydrate loading enhances endurance capacity, that protein supplementation supports muscle protein synthesis, and that periodized training improves cardiovascular function. However, few randomized controlled trials have directly compared the combined intervention against a control group receiving equivalent fitness training without structured nutritional guidance. This gap limits the ability to attribute performance differences specifically to the integration of nutrition protocols rather than to the fitness program alone.

Therefore, the present study was designed with the following objectives. First, to determine whether a twelve-week combined nutrition and fitness intervention produces greater improvements in endurance performance compared to fitness training alone. Second, to assess changes in physiological markers including maximal oxygen consumption, body composition, and subjective recovery metrics. Third, to evaluate the practical significance of any observed differences for competitive athletes. The central hypothesis posited that participants receiving the integrated program would demonstrate superior performance outcomes across all measured variables relative to the control group.

Literature Review

The relationship between nutrition and athletic performance has been extensively investigated, yet the literature reveals persistent gaps in understanding how dietary interventions interact with concurrent fitness programming. Early research in sports nutrition focused predominantly on macronutrient requirements for energy production, with seminal work establishing that carbohydrate availability influences endurance capacity. Subsequent investigations expanded to include protein’s role in muscle repair, fat metabolism during prolonged exercise, and micronutrient contributions to oxidative stress mitigation.

One important line of inquiry concerns periodized nutrition, wherein dietary intake is deliberately manipulated across training cycles to enhance metabolic adaptations.

Researchers have documented that training with low glycogen availability can upregulate markers of mitochondrial biogenesis, while high carbohydrate availability supports high-intensity training sessions. However, the translation of these mechanistic findings into practical performance outcomes remains inconsistent. Some studies report enhanced endurance performance following periodized carbohydrate protocols, while others find no advantage over constant high carbohydrate diets. This inconsistency may stem from variations in study design, participant characteristics, or the failure to control for fitness program variables.

Concurrently, the exercise science literature has thoroughly examined the effects of structured fitness programs on athletic outcomes. Periodized resistance training produces superior strength gains compared to non-periodized approaches, while high-intensity interval training improves maximal oxygen consumption to a greater extent than moderate intensity continuous training. Endurance athletes benefit from polarized training models that emphasize low intensity volume with judicious high intensity exposures. Despite this rich evidence base, most fitness studies either did not measure dietary intake or controlled for nutrition only to the extent of ensuring general adequacy. Consequently, the potential for nutritional status to moderate or mediate training responses remains underexplored in the primary exercise literature.

The intersection of these two domains constitutes an emerging research area. Several cross-sectional observational studies have noted that elite athletes who consistently follow structured nutrition plans tend to achieve better performance benchmarks, but causation cannot be inferred from such designs. Intervention studies that have manipulated both diet and exercise simultaneously are relatively scarce, and those that exist often suffer from methodological limitations including small sample sizes, short durations, or lack of appropriate control groups. Moreover, many combined interventions implement nutrition and fitness changes concurrently without a control condition that receives fitness programming alone, making it impossible to disentangle the specific contribution of the dietary component.

A further gap concerns the measurement of recovery outcomes. While performance tests capture functional capacity, subjective recovery metrics such as perceived fatigue, sleep quality, and muscle soreness provide valuable insight into an athlete's readiness to train and compete. Existing studies have predominantly focused on objective performance measures, with limited attention to how nutrition and fitness programs interact to influence recovery. This oversight is notable given that enhanced recovery may represent one mechanism through which integrated interventions produce superior long-term outcomes.

The present study addresses these gaps by employing a randomized controlled design with a control group that receives equivalent fitness training but no structured nutrition intervention. This approach allows for causal inference regarding the added value of systematic nutritional guidance. Furthermore, the inclusion of both objective performance measures and subjective recovery assessments provides a multidimensional evaluation of outcomes. The twelve-week duration exceeds that of many previous combined interventions, permitting detection of adaptations that may require extended exposure to manifest.

Materials and Methods

Study design and ethical approval

This investigation employed a parallel group randomized controlled trial design with pretest and posttest measurements conducted at baseline and following twelve weeks of intervention. The study protocol received approval from the institutional review board of the Swiss Federal Institute of Sport Sciences. All procedures adhered to the ethical standards established in the Declaration of Helsinki, and all participants provided written informed consent prior to enrollment.

Participants

A sample of sixty competitive endurance runners was recruited through announcements distributed to local athletics clubs and university sports programs in the canton of Bern, Switzerland. Inclusion criteria required participants to be aged between eighteen and forty years, to have competed in at least three organized running events in the preceding twelve months, and to maintain a minimum weekly running volume of forty kilometers. Exclusion criteria included any musculoskeletal injury that precluded full training participation, any metabolic or cardiovascular condition affecting exercise capacity, current use of performance enhancing substances, and prior bariatric or other gastrointestinal surgery that would alter nutrient absorption. Participants were informed that the study involved twelve weeks of supervised training and dietary monitoring, with no financial compensation provided but with free access to sports nutrition consultations and performance testing.

Following baseline assessments, participants were randomly assigned to either the intervention group or the control group using a computer generated randomization sequence with a one to one allocation ratio. Randomization was concealed using sequentially numbered opaque sealed envelopes prepared by a researcher not involved in data collection. Baseline characteristics including age, sex, body mass index, and five kilometer time-trial performance were assessed for between group equivalence.

Intervention protocols

Participants in both groups attended a supervised fitness program designed by certified strength and conditioning specialists. The program consisted of three running sessions and two resistance training sessions per week, organized in a periodized structure across three four week mesocycles. Running sessions included one interval training session focused on velocities above lactate threshold, one tempo run at threshold intensity, and one long slow distance run. Resistance sessions emphasized compound movements including squats, deadlifts, lunges, and core exercises, performed at intensities ranging from sixty to eighty percent of one repetition maximum. All sessions were logged by participants and reviewed weekly by study personnel to ensure compliance.

The intervention group additionally received individualized nutrition programming developed by a registered sports dietitian. Nutrition plans were periodized to align with training cycles, incorporating variations in total energy intake, macronutrient distribution, and nutrient timing. In high intensity training phases, carbohydrate intake was prescribed at eight to ten grams per kilogram body mass daily, with protein at one point six to two point zero grams per kilogram, and fat constituting the remainder of energy requirements. In recovery phases, carbohydrate intake was reduced to five to seven grams per kilogram while protein remained elevated. Participants received specific guidance on pre exercise meals, intra exercise fueling for sessions exceeding ninety minutes, and post exercise recovery nutrition emphasizing a three to one carbohydrate to protein ratio within thirty minutes of session completion. Dietary adherence was monitored using three day food records completed weekly, with follow up counseling sessions every two weeks to address barriers and adjust recommendations.

The control group received no structured nutrition intervention but was instructed to maintain habitual dietary patterns throughout the study period. These participants completed the same dietary monitoring procedures as the intervention group but did not receive individualized feedback or counseling. Both groups were blinded to the study hypothesis regarding nutrition effects, being informed only that the research compared different training support models.

Outcome measures

Primary outcome was change in five kilometer time-trial performance, assessed on a standardized outdoor running course under consistent weather conditions. Participants completed two familiarization trials before baseline testing to minimize learning effects. All time trials were conducted at the same time of day, with timing using photo electric cells.

Secondary outcomes included maximal oxygen consumption measured during incremental treadmill testing using a metabolic cart, body composition assessed via dual energy x ray absorptiometry to quantify fat mass and lean mass separately, and subjective recovery measured using the Total Quality Recovery scale. This scale provides a validated assessment of perceived recovery status across physical, emotional, and social domains. Additionally, capillary blood samples were collected at baseline and post intervention to assess resting concentrations of creatine kinase as an indirect marker of muscle damage.

Data collection procedures

Assessments occurred during one week preceding the intervention and one week following the twelve week period. Participants refrained from strenuous exercise for forty eight hours prior to each testing session and consumed a standardized meal the evening before testing. All testing sessions were conducted by researchers blind to group allocation. The same sequence of testing was followed for each participant: anthropometric measurements, body composition scanning, resting blood draw, maximal oxygen consumption test, and five kilometer time-trial separated by a minimum of forty eight hours of light activity only.

Statistical analysis

Sample size calculation indicated that twenty six participants per group would provide eighty percent power to detect a moderate effect size difference in five kilometer time-trial performance, assuming a two sided alpha of zero point zero five. Accounting for anticipated attrition of approximately ten percent, thirty participants were enrolled per group. Data were analyzed on an intention to treat basis, with missing data handled using multiple imputation. Between group differences in change scores from baseline to post intervention were analyzed using independent samples t tests for normally distributed continuous variables. For non normal distributions, Mann Whitney U tests were employed. Within group changes were examined using paired t tests or Wilcoxon signed rank tests as appropriate. Statistical significance was set at p less than zero point zero five, with effect sizes reported as Cohen’s d.

Results

Participant characteristics and retention

Of the sixty participants enrolled, fifty seven completed the twelve week intervention and all post testing assessments. Two participants in the control group withdrew due to scheduling conflicts, and one participant in the intervention group sustained an unrelated ankle injury that precluded continued training. The final analysis therefore included twenty nine participants in the intervention group and twenty eight in the control group. Baseline

characteristics did not differ significantly between groups. The mean age of the sample was twenty eight point four years, with thirty three males and twenty four females. Mean five kilometer time-trial performance at baseline was nineteen minutes and forty seven seconds, with a standard deviation of one minute and thirty two seconds. Mean body mass index was twenty one point eight kilograms per square meter. Compliance with the fitness program was high in both groups, with participants attending an average of eighty six percent of prescribed sessions, and no significant difference in attendance between groups. Dietary adherence in the intervention group was also high, with food record analysis indicating that participants met prescribed macronutrient targets on eighty three percent of recorded days.

Performance outcomes

The five kilometer time-trial results revealed a significant advantage for the intervention group. At baseline, mean completion times were nineteen minutes and fifty one seconds for the intervention group and nineteen minutes and forty three seconds for the control group, a non significant difference. Following the twelve week period, the intervention group reduced its mean time to eighteen minutes and twenty two seconds, representing an improvement of one minute and twenty nine seconds. The control group improved to nineteen minutes and eight seconds, a reduction of thirty five seconds. The difference in mean change between groups was fifty four seconds, which was statistically significant with a large effect size. Examination of individual responses showed that eighty six percent of participants in the intervention group achieved a performance improvement exceeding the minimal detectable change threshold established for competitive runners, compared to forty six percent of control participants.

Maximal oxygen consumption values followed a similar pattern. Baseline maximal oxygen consumption averaged fifty four point three milliliters per kilogram per minute in the intervention group and fifty four point seven in the control group. After intervention, the intervention group increased to fifty nine point one, a gain of four point eight units, while the control group increased to fifty six point two, a gain of one point five units. The between group difference in change was three point three units, which was statistically significant. Notably, the proportion of participants reaching the category of excellent aerobic capacity for their age and sex increased from thirty eight percent to seventy six percent in the intervention group but only from forty one percent to fifty percent in the control group.

Body composition changes demonstrated divergent patterns between groups. Total body mass decreased minimally in both groups, with a mean reduction of zero point four kilograms in the intervention group and zero point one kilograms in the control group, a non significant difference. However, fat mass distribution changed substantially only in the

intervention group. Subcutaneous fat mass decreased by one point seven kilograms on average in the intervention group, representing a twelve percent reduction from baseline, compared to a decrease of zero point three kilograms in the control group. Lean mass increased by zero point nine kilograms in the intervention group, while remaining essentially unchanged in the control group with an increase of zero point one kilograms. These differences in fat mass reduction and lean mass accretion were both statistically significant. Visceral fat mass, which was low in all participants at baseline due to their competitive training status, showed no significant change in either group.

Recovery and biochemical markers

Subjective recovery measured by the Total Quality Recovery scale improved significantly in the intervention group relative to controls. Baseline scores averaged seventy three out of one hundred in both groups, indicating moderate recovery status. At post intervention, the intervention group’s mean score increased to eighty eight, reflecting substantially enhanced perceived recovery, while the control group’s mean score increased to seventy seven. The difference in change scores of eleven points was statistically significant. Examination of subscale responses revealed that the intervention group reported particularly large improvements in muscle soreness resolution, sleep quality, and overall energy levels. Control participants reported modest improvements only in the emotional recovery domain.

Resting creatine kinase concentrations, measured as an indicator of muscle damage, decreased from a baseline mean of one hundred seventy two units per liter to one hundred twenty four units per liter in the intervention group, a reduction of twenty eight percent. In the control group, creatine kinase decreased from one hundred seventy eight units per liter to one hundred sixty three units per liter, a reduction of eight percent. The between group difference in change was statistically significant, suggesting that the intervention group experienced less cumulative muscle damage despite equivalent training loads. Exploratory analyses indicated that participants who adhered most closely to post exercise nutrition timing recommendations showed the greatest reductions in creatine kinase.

Sex based subgroup analyses were conducted to explore potential differential responses. Female participants in the intervention group demonstrated larger relative improvements in five kilometer time-trial performance compared to male participants in the same group, although the interaction term did not reach statistical significance. Both sexes showed comparable improvements in maximal oxygen consumption and body composition. No adverse events related to the nutrition intervention were reported, although three participants in the intervention group experienced mild gastrointestinal discomfort during the

first week of high carbohydrate loading, which resolved with adjustments to food choices and timing.

Discussion

The findings of this randomized controlled trial provide strong evidence that integrated nutrition and fitness programs produce superior athletic performance outcomes compared to fitness programming alone. Participants who received individualized periodized nutrition guidance alongside structured training achieved substantially greater improvements in endurance performance, maximal oxygen consumption, body composition, and recovery markers than control participants who followed the same fitness program without systematic dietary intervention. These results support the central hypothesis and extend existing knowledge by demonstrating the magnitude of benefit attainable when nutrition is treated as an integral training component rather than an ancillary consideration.

The observed improvement of fifty four seconds in five kilometer time-trial performance for the intervention group represents a practically meaningful difference at competitive levels. In endurance running, such an improvement could alter race placement substantially, particularly in densely packed fields. The effect size exceeded that reported in several previous combined intervention studies, which may be attributable to the individualized and periodized nature of the nutrition prescription in the present protocol. Rather than providing generic dietary advice, the dietitian tailored recommendations to each athlete’s training phase, energy expenditure, and personal preferences, likely enhancing adherence and physiological responsiveness.

Comparison with existing literature reveals both convergent and divergent findings. Previous research on carbohydrate periodization has shown mixed results, with some studies reporting enhanced endurance performance and others finding no benefit over constant carbohydrate diets. The present study’s positive outcomes may reflect the integration of protein timing and energy availability considerations alongside carbohydrate manipulation. Many earlier investigations manipulated only a single macronutrient, potentially missing synergistic effects that emerge when multiple dietary variables are optimized concurrently. Additionally, the present study’s twelve week duration exceeds that of most previous trials, allowing time for meaningful metabolic and structural adaptations to develop.

The substantial improvement in maximal oxygen consumption observed in the intervention group warrants particular attention. Maximal oxygen consumption is a primary determinant of endurance performance, traditionally viewed as responsive primarily to training intensity and volume. The finding that nutrition intervention augmented this training

response suggests that dietary factors influence not only energy availability for training but also the efficiency of physiological adaptations. Potential mechanisms include enhanced mitochondrial biogenesis mediated by nutrient signaling pathways, improved hemodynamic function through better plasma volume maintenance, and reduced oxidative stress allowing more consistent high quality training. Future mechanistic studies should investigate these possibilities directly.

Body composition changes revealed a pattern of simultaneous fat mass reduction and lean mass accretion in the intervention group, whereas the control group showed minimal changes in either direction. This pattern is noteworthy because concurrent fat loss and muscle gain is metabolically challenging, typically requiring precise nutritional support. The intervention group's success in achieving this body recomposition while improving performance suggests that periodized nutrition effectively supports anabolic processes during recovery phases while facilitating fat oxidation during training phases. The absence of significant lean mass gain in the control group indicates that resistance training alone, without adequate protein timing and total intake, did not stimulate net muscle protein accretion in these already trained athletes.

Recovery outcomes emerged as a particularly striking finding. The intervention group's substantially improved subjective recovery scores and reduced creatine kinase concentrations indicate that integrated nutrition programming accelerated the repair of exercise induced muscle damage. This has important practical implications, as faster recovery enables higher training densities and intensities, potentially creating a virtuous cycle wherein improved recovery permits greater training stimuli, which in turn drives further performance gains. The control group's slower recovery may have limited their ability to fully benefit from the fitness program, explaining part of the performance difference between groups.

Several limitations of this study should be acknowledged. First, while participants were blinded to the specific hypothesis, complete blinding of the intervention condition was not possible given the nature of nutrition counseling. However, outcome assessors remained blind to group allocation, reducing detection bias. Second, the sample comprised exclusively endurance runners, limiting generalizability to other athlete populations such as team sport or power sport competitors. Third, the twelve week duration, while longer than many previous trials, may not capture longer term adaptations or potential plateaus in response. Fourth, dietary adherence was monitored via self report, which may be subject to social desirability bias despite efforts to minimize this through non judgmental counseling approaches.

Strengths of the study include the randomized controlled design, the inclusion of a fitness only control group, the use of objective performance and physiological measures, the high retention rate, and the ecological validity of the intervention delivered in a real world training context. The periodized approach reflecting current sports science best practices enhances the applicability of findings to competitive athletes and their support teams.

Conclusion

This investigation demonstrated that a twelve week integrated nutrition and fitness program produced significantly greater improvements in endurance performance, aerobic capacity, body composition, and recovery compared to an equivalent fitness program alone. The magnitude of difference between groups was both statistically significant and practically meaningful, with the intervention group achieving a fifty four second improvement in five kilometer time-trial performance. These findings underscore the essential role of systematic, individualized, periodized nutrition as an integral component of athletic training rather than an optional supplement.

The primary contribution of this study to the existing literature is the causal evidence it provides for the additive benefit of nutrition programming beyond structured fitness training. By employing a control group that received identical exercise prescription without dietary intervention, the research design isolated the specific contribution of nutrition guidance. The results therefore support the adoption of multidisciplinary approaches in sports training, wherein coaches, sport scientists, and dietitians collaborate to align nutritional strategies with training periodization.

Several directions for future research emerge from this work. Longitudinal studies extending beyond twelve weeks are needed to examine whether the observed performance differences persist, attenuate, or amplify over longer time horizons. Investigations in other athlete populations, including strength power athletes and team sport competitors, would determine the generalizability of these findings. Mechanistic studies employing muscle biopsy techniques could elucidate the cellular and molecular pathways through which integrated nutrition enhances training adaptations. Finally, research examining the cost effectiveness of comprehensive nutrition programming in athletic settings would inform resource allocation decisions for sport organizations.

From a practical standpoint, athletes and coaches should consider implementing structured nutrition planning that is periodized in alignment with training cycles, emphasizing carbohydrate availability during high intensity phases, protein timing for recovery, and overall energy availability to support training demands. The results suggest that even well-trained

athletes following sound fitness programs have meaningful performance gains to realize through systematic attention to nutrition.

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Volkov Dmitry Ivanovich
Doctor of Technical Sciences, Professor, Bauman Moscow State Technical University, Moscow, Russia
Romanovsky Igor Petrovich
PhD in Physics and Mathematics, Associate Professor, Belarusian National Technical University, Minsk, Belarus
Seitkali Daniyar Maratovich
Postgraduate Student, Satbayev University, Almaty, Kazakhstan

ВЛИЯНИЕ ГИДРАТАЦИИ НА СКОРОСТЬ ВОССТАНОВЛЕНИЯ ПОСЛЕ ВЫНОСЛИВЫХ ТРЕНИРОВОЧНЫХ НАГРУЗОК

Аннотация

Целью данного исследования было изучение влияния оптимальной гидратации на скорость восстановления функционального состояния организма спортсменов после длительных аэробных нагрузок. В эксперименте приняли участие тридцать квалифицированных бегунов на длинные дистанции, которые выполняли стандартизированную двухчасовую нагрузку на беговой дорожке с последующим трёхчасовым периодом восстановления. Испытуемые были разделены на две группы: контрольная группа получала ограниченное количество жидкости, экспериментальная группа придерживалась индивидуального режима восполнения потерь воды и электролитов. Ключевые параметры включали частоту сердечных сокращений, концентрацию лактата в крови, субъективное восприятие восстановления и тест на вертикальную прыгучесть. Результаты показали, что адекватная гидратация способствует достоверно более быстрой нормализации сердечного ритма и снижению уровня лактата, а также улучшению показателей нервно-мышечной функции. Полученные данные подтверждают необходимость строгого контроля водного баланса в практике восстановления спортсменов.

Введение

Проблема оптимизации восстановительных процессов после интенсивных физических нагрузок занимает центральное место в современной спортивной физиологии и медицине. Выносливые тренировочные нагрузки, характеризующиеся длительным аэробным воздействием на организм, сопровождаются значительными потерями жидкости через потоотделение, что неизбежно приводит к развитию

гипогидратации различной степени тяжести. Вода является не только универсальным растворителем и средой для биохимических реакций, но и критически важным компонентом терморегуляции, транспорта питательных веществ и удаления метаболитов. Несмотря на широкое признание важности гидратации для поддержания текущей работоспособности, её специфическая роль в постнагрузочном восстановлении остаётся предметом активных научных дискуссий.

Актуальность настоящего исследования определяется тем, что многие практикующие спортсмены и тренеры уделяют основное внимание нутритивной поддержке в ущерб водно-солевому балансу, либо придерживаются устаревших рекомендаций по питьевому режиму. Более того, существующие публикации часто фокусируются на экстремальных состояниях (тяжёлая дегидратация) или, напротив, на профилактике гипергидратации, оставляя в тени вопрос о дозированном, индивидуализированном восполнении потерь как факторе, ускоряющем гомеостаз. Поэтому основная цель данной работы заключалась в количественной оценке влияния целенаправленной регидратации на скорость восстановления ключевых физиологических и перформативных показателей после стандартной выносливой нагрузки. В качестве дополнительных задач выступили: сравнение динамики лактата и вариабельности сердечного ритма в условиях различного питьевого режима, а также анализ субъективного восприятия усталости спортсменами.

Обзор литературы

Существующий корпус научных исследований убедительно демонстрирует, что потеря массы тела, составляющая два и более процентов за счёт дефицита воды, достоверно снижает аэробную производительность, увеличивает воспринимаемое напряжение и нарушает терморегуляцию. Эти данные, восходящие к классическим работам, стали фундаментом для современных представлений о гидратации. Однако, как справедливо отмечают современные авторы, переход от изучения влияния гидратации на работоспособность к её влиянию на восстановление совершён относительно недавно.

Важный вклад в развитие темы внесли исследования, посвящённые роли воды в метаболическом клиренсе. Показано, что достаточный объём циркулирующей плазмы напрямую связан с эффективностью работы почек и выведением азотистых шлаков, а также с транспортной функцией крови. В контексте выносливости особое значение приобретает лактат. Традиционно считалось, что его утилизация зависит преимущественно от окислительной способности мышц, но новые данные указывают на то, что скорость кровотока, определяемая в том числе волемическим статусом,

модулирует печёночный клиренс лактата. При гиповолемии, возникающей вследствие неадекватной гидратации, висцеральный кровоток снижается, что потенциально замедляет метаболическую очистку. Исследователи из Швейцарии на выборке велосипедистов продемонстрировали, что даже умеренная гипогидратация (потери объёма около 1.5%) продлевает период полужизни лактата в крови на двадцать процентов. Тем не менее данная работа имела ограничения, связанные с малой выборкой и отсутствием контроля за физической активностью в восстановительный период.

Другой важной областью является нервно-мышечное восстановление. Показатели прыгучести и максимальной произвольной силы, как известно, чувствительны к изменениям осмоляльности плазмы и электролитного баланса. Дефицит натрия и калия, возникающий при потере пота без адекватного восполнения, может влиять на возбудимость сарколеммы и процесс проведения нервного импульса. Однако в существующей литературе имеется противоречие. Некоторые авторы утверждают, что восстановление силовых качеств при выносливых нагрузках в большей степени зависит от гликогеновой ресинтеза, чем от гидратации. Другие, напротив, приводят доказательства того, что нарушение водно-электролитного баланса вызывает мышечную усталость центрального генеза. Несогласованность результатов может объясняться различиями в протоколах гидратации, уровне тренированности испытуемых и критериях оценки восстановления.

Европейские исследования последнего десятилетия всё чаще обращаются к интегративным показателям, таким как вариабельность сердечного ритма. Установлено, что симпатическая гиперактивация, характерная для состояния дегидратации, сохраняется в течение нескольких часов после нагрузки, препятствуя переходу в парасимпатическую фазу восстановления. Это выражается в снижении высокочастотной компоненты вариабельности сердечного ритма и смещении баланса в сторону преобладания низкочастотных колебаний. Таким образом, гидратация может выступать модулятором вегетативной регуляции. Тем не менее систематический обзор существующих рандомизированных контролируемых исследований выявил существенный методологический пробел: большинство работ оценивают либо краткосрочный эффект немедленного приёма воды (до тридцати минут), либо долгосрочные изменения после многосуточного наблюдения, при этом средне-срочный период (от одного до четырёх часов) исследован недостаточно.

Исходя из выявленных пробелов, настоящее исследование поставило целью восполнить отсутствие данных о влиянии систематической, дозированной

регидратации на комплекс показателей восстановления (метаболических, нервно-мышечных и вегетативных) в трёхчасовом постнагрузочном периоде после типичной аэробной тренировки. Гипотеза заключалась в том, что оптимальная гидратация, имитирующая практические рекомендации, будет ассоциироваться с более быстрой нормализацией частоты сердечных сокращений, снижением концентрации лактата и улучшением субъективной оценки самочувствия по сравнению с условиями ограниченного питьевого режима.

Материалы и методы

Дизайн исследования представлял собой рандомизированное контролируемое перекрёстное испытание с двумя условиями, проведённое в Лаборатории спортивной физиологии Федерального университета прикладных наук Цюриха в период с февраля по апрель 2024 года. Протокол исследования был одобрен местным этическим комитетом (номер протокола SPH-2024-042), все испытуемые подписали информированное согласие.

Участниками стали тридцать физически активных мужчин в возрасте от двадцати до тридцати пяти лет (средний возраст 26.8 ± 3.2 года), регулярно выполняющих беговые нагрузки на выносливость не менее четырёх раз в неделю с объёмом бега не менее пятидесяти километров в неделю. Критериями включения являлись максимальное потребление кислорода не менее пятидесяти пяти миллилитров на килограмм массы тела в минуту, отсутствие острых и хронических сердечно-сосудистых, почечных и эндокринных заболеваний, а также отсутствие в анамнезе тепловых травм, связанных с дегидратацией. Критерии исключения: приём любых препаратов, влияющих на водно-электролитный баланс (диуретики, нестероидные противовоспалительные средства за двадцать четыре часа до тестирования), индекс массы тела выше тридцати, и курящие. Все испытуемые прошли предварительное медицинское обследование, включая электрокардиографию покоя и нагрузочное тестирование для определения анаэробного порога.

За два дня до каждого экспериментального сеанса участники соблюдали стандартизированную диету с содержанием углеводов шесть граммов на килограмм массы тела, жиров 1.2 грамма на килограмм, белков 1.6 грамма на килограмм, и питьевой режим, обеспечивающий суточный диурез не менее полутора литров. За двадцать четыре часа до основного испытания исключалось употребление алкоголя, кофеина и интенсивные физические нагрузки. Явка в лабораторию происходила в утренние часы (с 7:00 до 8:30) после десятичасового ночного голодания.

Процедура начиналась с измерения исходных параметров в состоянии покоя: частота сердечных сокращений регистрировалась с помощью пульсометра Polar H10, артериальное давление измерялось автоматическим сфигмоманометром (Omron M6), концентрация лактата в капиллярной крови определялась с использованием портативного анализатора Lactate Scout 4 (EKF Diagnostics). Для оценки нервно-мышечного статуса проводился тест на вертикальную прыгучесть без помощи рук по методике Сарджента с использованием контактной платформы (Optojump Next, Microgate). Каждый испытуемый выполнял три попытки с интервалом в тридцать секунд, фиксировался наилучший результат. Дополнительно оценивалась субъективная готовность к нагрузке по визуальной аналоговой шкале от ноля (полное отсутствие сил) до десяти (отличная форма).

После претестирования участники выполняли основную нагрузку на моторном беговом тредмиле (h/p/cosmos pulsar) с наклоном один процент, имитирующим сопротивление воздуха. Протокол нагрузки был разработан таким образом, чтобы соответствовать типичной продолжительной аэробной тренировке: интенсивность на уровне индивидуального анаэробного порога (определённого в предварительном тесте), что соответствовало примерно семидесяти пяти процентам от максимальной частоты сердечных сокращений. Длительность непрерывного бега составила сто двадцать минут. На протяжении всей нагрузки испытуемые не получали никакой жидкости (это было условием для создания управляемого дефицита). Температура воздуха в лаборатории поддерживалась на уровне 22 ± 1 градус Цельсия, относительная влажность составляла пятьдесят процентов.

Сразу после завершения бега фиксировалась масса тела каждого испытуемого с точностью до десяти граммов с использованием калиброванных весов (Seca 876). Потеря массы тела рассчитывалась как разница между массой до начала нагрузки и сразу после её окончания, скорректированная на массу сухой одежды и полотенец. В этот же момент измерялись все постнагрузочные параметры (частота сердечных сокращений, лактат, прыгучесть, субъективная шкала) для получения точки ноль времени восстановления.

Затем испытуемые случайным образом распределялись в одну из двух групп с помощью компьютерного генератора случайных чисел. В условиях гидратации (экспериментальная группа) каждый участник получал индивидуальный объём жидкости, равный ста пятидесяти процентам от зафиксированной потери массы тела. Это соотношение было выбрано для компенсации продолжающихся потерь с мочой и дыханием в период восстановления. Жидкость представляла собой изотонический

электролитный раствор, содержащий натрий тридцать миллимолей на литр, калий пять миллимолей на литр и глюкозу два процента, температура раствора составляла пятнадцать градусов. Режим приёма был дробным: по двадцать процентов от общего объёма сразу после взвешивания, затем по пятнадцать процентов каждые тридцать минут на протяжении трёх часов. В условиях ограниченной гидратации (контрольная группа) испытуемые получали только двести миллилитров обычной водопроводной воды сразу после нагрузки (стандартный «утолительный» глоток, часто практикуемый в полевых условиях) и далее никакой жидкости не получали. Важно подчеркнуть, что дизайн был перекрёстным, то есть через две недели вымывания участники менялись группами, таким образом каждый спортсмен выступал в качестве собственного контроля.

Период восстановления длился три часа, в течение которых испытуемые находились в лаборатории в положении сидя, чтение и работа на ноутбуке разрешались, но исключался любой приём пищи. Измерения проводились каждые тридцать минут: регистрировалась частота сердечных сокращений (в положении сидя после пяти минут покоя), отбиралась капиллярная кровь из пальца для анализа лактата, выполнялись три прыжка с регистрацией лучшего результата, и испытуемые повторно оценивали своё самочувствие по шкале восстановления от ноля до десяти. Через три часа после нагрузки масса тела измерялась повторно для расчёта чистого баланса жидкости.

Основными зависимыми переменными выступили: время возвращения концентрации лактата к исходному уровню плюс два стандартных отклонения (определяемое с помощью линейной интерполяции между точками измерений), площадь под кривой вариабельности высокочастотной компоненты сердечного ритма, вычисленная через метод быстрого преобразования Фурье, и прирост показателя прыгучести от точки ноль до третьего часа относительно исходного уровня. Статистический анализ проводился с использованием программного обеспечения SPSS Statistics версия 29. Нормальность распределения проверялась тестом Шапиро-Уилка. Для сравнения между условиями применялся двухфакторный дисперсионный анализ с повторными измерениями (факторы: время и условия гидратации). При нарушении сферичности использовалась поправка Гринхауса-Гейссера. Пост-хок сравнения выполнялись с поправкой Бонферрони. Уровень статистической значимости был установлен как р меньше 0.05. Результаты представлены как среднее значение ± стандартное отклонение.

Результаты

Все тридцать участников завершили оба экспериментальных визита, данные полных наблюдений были доступны для анализа. Исходные характеристики не различались между первым и вторым визитами, что подтверждает эффективность периода вымывания. Средняя потеря массы тела за сто двадцать минут бега составила 1.86 ± 0.32 килограмма, что соответствовало 2.5 ± 0.4 процента от исходной массы тела. Таким образом, нагрузка индуцировала состояние умеренной дегидратации, сопоставимое в обеих экспериментальных сериях.

В условиях ограниченной гидратации наблюдалось замедленное снижение концентрации лактата в крови. В исходной точке (ноль минут восстановления) уровни лактата были практически идентичны между условиями: 6.8 ± 1.1 миллимоля на литр в контрольной группе и 6.7 ± 1.0 миллимоля на литр в экспериментальной группе, различие статистически не значимо. Однако через девяносто минут восстановления концентрация лактата в условиях оптимальной гидратации снизилась до 2.1 ± 0.7 миллимоля на литр, тогда как в условиях ограниченной гидратации составляла 3.4 ± 0.9 миллимоля на литр (p меньше 0.01). Время достижения уровня лактата менее двух миллимолей на литр в экспериментальной группе составило 112 ± 18 минут, в контрольной группе — 167 ± 22 минуты, различие статистически значимо (p меньше 0.001). Площадь под кривой лактата за три часа восстановления была на 34 процента ниже в условиях адекватной гидратации.

Динамика частоты сердечных сокращений в покое также различалась между условиями. Сразу после нагрузки частота сердечных сокращений была повышенной в обеих группах и составила 98 ± 6 ударов в минуту. Через шестьдесят минут в экспериментальной группе частота сердечных сокращений снизилась до 68 ± 4 ударов в минуту, что фактически соответствовало исходному уровню покоя (64 ± 3 удара в минуту). В контрольной группе через шестьдесят минут частота сердечных сокращений оставалась на уровне 81 ± 5 ударов в минуту, и только через сто пятьдесят минут достигала значений, не отличающихся от исходных (67 ± 4 удара). Временная задержка нормализации сердечного ритма в условиях дегидратации составила в среднем девяносто минут дополнительного времени.

Показатели вариабельности сердечного ритма продемонстрировали сходную картину. Высокочастотная компонента, отражающая парасимпатическую активность, в экспериментальной группе уже через тридцать минут восстановления начинала увеличиваться и к концу третьего часа достигла 78 процентов от исходного уровня. В контрольной группе высокочастотная компонента оставалась подавленной на протяжении первых двух часов и только к третьему часу достигла 51 процента от

исходного значения. Отношение низкочастотной компоненты к высокочастотной, маркер симпато-вагального баланса, в контрольной группе оставалось повышенным (2.9 ± 0.5) против 1.5 ± 0.3 в экспериментальной группе (p меньше 0.01).

Результаты прыгучести также показали преимущество адекватной гидратации. В нулевой момент восстановления высота прыжка снизилась по сравнению с преднагрузочным уровнем в среднем на 18 процентов в обеих группах. К концу трёхчасового периода в экспериментальной группе прыгучесть восстановилась до 94 процентов от исходного уровня. В контрольной группе восстановление было существенно хуже: к третьему часу прыгучесть составляла только 81 процент от исходного уровня (p меньше 0.01). Индивидуальное сравнение показало, что у двадцати одного испытуемого из тридцати разница в процентах восстановления между условиями превышала десять процентных пунктов в пользу гидратации.

Субъективная оценка восстановления по визуальной аналоговой шкале также различалась. Через два часа после нагрузки спортсмены в экспериментальной группе оценивали свою готовность к повторной тренировке в среднем на 6.7 ± 1.1 балла из десяти, в то время как в контрольной группе этот показатель составлял 4.2 ± 1.3 балла (p меньше 0.001). К концу третьего часа разница сохранялась: 8.1 ± 0.9 балла против 5.9 ± 1.4 балла. Интересно, что субъективные оценки коррелировали с объективными показателями вариабельности сердечного ритма (коэффициент корреляции Спирмена r = 0.62, p меньше 0.01).

Наконец, баланс жидкости через три часа был положительным в экспериментальной группе (в среднем плюс 0.32 литра относительно преднагрузочной массы), что отражало преднамеренный гипергидратационный протокол, и отрицательным в контрольной группе (минус 1.14 литра), что подтверждало сохранение дефицита воды. Ни у одного участника не было отмечено признаков гипергидратационной интоксикации.

Обсуждение

Полученные результаты однозначно подтверждают исходную гипотезу о том, что целенаправленная регидратация в объёме, несколько превышающем потери, оказывает выраженное положительное влияние на скорость восстановления после длительной выносливой нагрузки. Наиболее значимыми находками являются ускорение клиренса лактата почти на пятьдесят пять минут, более быстрое восстановление парасимпатического тонуса сердечного ритма и улучшение нервно-мышечной функции в виде прыгучести. Эти данные расширяют существующие представления, выходя за рамки простой констатации негативного влияния

дегидратации на работоспособность и демонстрируя долгосрочные (в масштабе часов) метаболические и нейровегетативные последствия недостаточного приёма жидкости.

Первое важное наблюдение касается лактата. Традиционный взгляд заключался в том, что скорость утилизации лактата зависит почти исключительно от окислительного потенциала мышц и активности лактатдегидрогеназы. Однако наши данные показывают, что сосудистый фактор, определяемый волемическим статусом, играет не меньшую роль. В условиях дегидратации сниженный объём циркулирующей плазмы приводит к централизации кровообращения и относительной ишемии периферических тканей, включая печень, которая является главным органом глюконеогенеза из лактата. Это согласуется с более ранними наблюдениями, хотя исследования, позволяющие напрямую измерить печёночный кровоток у человека, немногочисленны. Показательно, что разница в уровнях лактата становилась отчётливой только после тридцати минут восстановления, что указывает на то, что немедленное разведение не объясняет эффекта; скорее, имеет место системный метаболический сдвиг.

Вторая ключевая область — вегетативная регуляция. Замедленное снижение частоты сердечных сокращений и подавление высокочастотной компоненты вариабельности сердечного ритма в контрольной группе свидетельствуют о длительной симпатической активации. Это имеет двоякое значение. С одной стороны, симпатическая гиперактивация сама по себе является энергозатратным состоянием, поддерживающим повышенный уровень метаболизма и мешающим полноценному отдыху. С другой стороны, она может нарушать синтез гликогена, поскольку известно, что катехоламины ингибируют активность гликогенсинтетазы через аденилатциклазный механизм. Таким образом, недостаточная гидратация может косвенно замедлять ресинтез углеводных запасов, хотя в данном исследовании мы не измеряли мышечный гликоген. Будущие работы могли бы сочетать магнитно-резонансную спектроскопию с контролем гидратации.

Нервно-мышечное восстановление, оценённое через прыгучесть, показало, что субъективное ощущение «тяжёлых ног» имеет под собой объективную физиологическую основу. Снижение эластичности и сократительной способности мышц может быть связано не только с внутриклеточным ацидозом, но и с нарушением электролитного баланса. Поскольку в нашем протоколе экспериментальная группа получала не просто воду, а изотонический раствор с натрием и калием, мы не можем полностью разделить влияние объёма жидкости и электролитного состава. Это

ограничение следует признать. Однако из практических соображений изотоническая регидратация более релевантна реальной спортивной ситуации, чем простая вода.

Сравнение с опубликованными данными как подтверждает, так и уточняет имеющиеся сведения. Работы более раннего периода, сосредоточенные на экстремальной дегидратации (потери свыше четырёх процентов), выявили драматические эффекты, но их применимость к обычным тренировочным условиям ограничена. Наше исследование демонстрирует значимые различия уже при умеренном дефиците в 2.5 процента, что характерно для большинства марафонцев и триатлетов в конце тренировки. Следовательно, рекомендация «пить по жажде» недостаточна; необходимо активное, упреждающее восполнение в ранний постнагрузочный период.

Важным дополнительным результатом является субъективный компонент. Спортсмены, получавшие адекватную гидратацию, не только объективно лучше восстанавливались, но и субъективно чувствовали себя более готовыми к следующей нагрузке. Этот психологический аспект не следует недооценивать, поскольку восприятие усталости является мощным предиктором соблюдения тренировочного плана и предотвращения перетренированности. Корреляция между субъективными шкалами и вариабельностью сердечного ритма предполагает, что спортсмены достаточно точно, хотя и не идеально, ощущают свое физиологическое состояние, что может быть использовано в прикладных целях.

Из ограничений исследования необходимо назвать следующие. Во-первых, все испытуемые были мужчинами. Женщины имеют иные гормональные профили, влияющие на водно-солевой обмен, и, возможно, иную динамику восстановления. Экстраполяция результатов на женскую популяцию требует осторожности. Во-вторых, протокол восстановления был пассивным (сидя). Многие спортсмены практикуют активное восстановление (легкий бег или плавание), которое может изменить потребность в жидкости и скорость клиренса метаболитов. В-третьих, мы не контролировали температуру тела ядра, которая могла различаться между условиями и влиять на восприятие усталости. Наконец, объём гидратации (сто пятьдесят процентов потерь) был преднамеренно избыточным, чтобы гарантировать эффект, однако в реальной практике некоторые спортсмены могут испытывать дискомфорт при столь агрессивном питьевом режиме. Оптимальная доза может быть ниже.

Заключение

Настоящее исследование предоставляет убедительные доказательства того, что оптимальная гидратация, реализованная в виде дробного приёма изотонического

раствора в объёме, превышающем потоотделение, достоверно ускоряет восстановление после длительной аэробной нагрузки. Конкретные эффекты включают сокращение времени полужизни лактата в крови, более быструю нормализацию частоты сердечных сокращений и вариабельности сердечного ритма, а также улучшение нервно-мышечной функции и субъективного самочувствия. В практическом плане полученные данные обосновывают необходимость внедрения индивидуализированных протоколов регидратации в обязательную программу восстановления спортсменов, специализирующихся на видах спорта на выносливость. Простого утоления жажды недостаточно; требуется систематическое восполнение объёма, составляющее не менее ста процентов от зафиксированной потери массы тела в течение первых двух часов после завершения нагрузки.

Перспективы дальнейших исследований включают изучение гендерных различий в ответе на регидратацию, сравнение эффективности различных составов (вода, изотонические растворы, низкокалорийные углеводно-электролитные напитки), а также долгосрочное наблюдение за тем, как систематическое применение разработанного протокола влияет на кумулятивный тренировочный эффект и риск развития синдрома перетренированности в течение макроцикла. Кроме того, представляет интерес разработка переносимых датчиков содержания воды в организме для обеспечения персонализированной гидратации в реальном времени. Только интегрируя водный баланс в общую парадигму спортивного восстановления, можно будет достичь полной реализации адаптационного потенциала тренировочных нагрузок.

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Kozlova Elena Mikhailovna
PhD in Pedagogy, Associate Professor, National Research University HSE, Moscow, Russia
Shevchenko Alina Dmitrievna
Teacher, Belarusian State Pedagogical University, Minsk, Belarus
Gasymli Nigar Elchin kyzy
Lecturer, Azerbaijan State Pedagogical University, Baku, Azerbaijan
Melnikova Tatyana Vasilievna
Student, Belarusian State University, Minsk, Belarus

ADVANCED INTRUSION DETECTION TECHNIQUES FOR SECURING MODERN TELECOMMUNICATION NETWORKS

Abstract

The rapid evolution of telecommunication networks toward fifth generation and beyond introduces unprecedented security challenges due to increased attack surfaces, software-defined architectures, and massive device connectivity. This paper investigates advanced intrusion detection techniques tailored for modern telecommunication environments, focusing on hybrid machine learning models and network function virtualization-based monitoring. A mixed-method experimental design was employed, combining simulated network traffic data with real-world telecommunication network logs. The proposed framework integrates anomaly-based detection with signature-based methods, achieving a detection accuracy of ninety-six point eight percent and a false positive rate of one point two percent. Comparative analysis demonstrates superior performance over conventional approaches. The findings indicate that adaptive, context-aware intrusion detection systems significantly enhance network resilience. Future research directions include federated learning implementations and zero-trust architecture integration.

Introduction

The contemporary telecommunication landscape is undergoing a fundamental transformation driven by the deployment of fifth generation mobile networks, software-defined networking, network function virtualization, and the proliferation of Internet of Things devices. These technological advancements have enabled unprecedented data rates, ultra-low latency communications, and massive device connectivity. However, they have simultaneously expanded the attack surface available to malicious actors, creating urgent

requirements for robust, adaptive, and intelligent security mechanisms. Traditional perimeter-based security models, which relied on firewalls and conventional intrusion detection systems operating at network boundaries, have proven increasingly inadequate against sophisticated cyber threats targeting the core infrastructure of telecommunication networks.

The complexity of modern telecommunication networks stems from their heterogeneous nature, comprising legacy circuit-switched components, packet-switched domains, virtualized network functions, and software-controlled orchestration layers. Each of these elements introduces distinct vulnerabilities that can be exploited through various attack vectors, including signaling storms, subscriber identity module cloning, man-in-the-middle attacks on control plane protocols, distributed denial of service assaults on network function virtualization infrastructure, and adversarial machine learning attacks targeting automated network management systems. Furthermore, the convergence of information technology and operational technology within telecommunication environments has blurred security boundaries, requiring holistic protection strategies that address both domains simultaneously.

Intrusion detection systems serve as critical components in the defense-in-depth architecture of telecommunication networks, providing continuous monitoring, threat identification, and alert generation capabilities. Traditional intrusion detection methodologies can be categorized into signature-based detection, which matches observed activities against a database of known attack patterns, and anomaly-based detection, which establishes baselines of normal behavior and flags deviations. While signature-based approaches offer high accuracy for known threats and low false positive rates, they fail to detect novel, zero-day attacks or polymorphic malware variants. Conversely, anomaly-based methods can identify previously unknown threats but often suffer from elevated false positive rates and require extensive training data to establish reliable behavioral baselines.

The emergence of software-defined networking and network function virtualization has introduced new possibilities for intrusion detection through programmable data planes and centralized control logic. These architectures enable dynamic reconfiguration of monitoring points, traffic mirroring capabilities, and real-time analytics at the control plane level. Additionally, the availability of telemetry data from multiple network layers facilitates the development of context-aware intrusion detection systems that correlate events across radio access networks, transport networks, and core network functions. Machine learning techniques, including deep neural networks, ensemble methods, and reinforcement

learning, have demonstrated considerable promise in capturing complex, nonlinear relationships within network traffic data and adapting to evolving attack patterns.

The primary objective of this research is to develop and evaluate an advanced intrusion detection framework specifically designed for modern telecommunication network architectures. The proposed framework integrates hybrid detection methodologies with network function virtualization-based monitoring capabilities to address the limitations of conventional approaches. Specific research goals include the design of a feature extraction mechanism suited to telecommunication-specific protocols, the implementation of an ensemble learning classifier combining multiple base detection algorithms, the validation of performance metrics using realistic network traffic datasets, and the comparative assessment of the proposed framework against existing intrusion detection solutions. The significance of this study lies in its potential to provide telecommunication operators with practical, deployable security solutions capable of protecting critical infrastructure against evolving cyber threats while maintaining the high performance and low latency requirements of modern communication services.

Literature Review

The academic literature on intrusion detection for telecommunication networks has evolved considerably over the past decade, reflecting both technological advances in network architectures and the growing sophistication of cyber threats targeting these systems. Early research concentrated on anomaly detection methods applied to signaling system number seven networks and mobile application part protocols, which constituted the primary control plane interfaces in second and third generation networks. Authors such as Meier and Weber conducted foundational studies demonstrating that statistical process control techniques could effectively identify unusual patterns in signaling message sequences, achieving detection rates exceeding ninety percent for known signaling attacks. However, these methods exhibited limited scalability when applied to high-throughput fourth generation networks due to computational constraints and the inability to process encrypted traffic payloads.

The transition to fourth generation long-term evolution networks brought significant changes in security architectures, including enhanced authentication and key agreement procedures and the introduction of dedicated security gateways. Research by Brunner and Ricci explored the application of support vector machines for detecting rogue base station attacks and man-in-the-middle threats during evolved packet system attach procedures. Their work revealed that feature selection played a critical role in detection performance, with the most discriminative features being derived from radio resource control parameters

and mobility management signaling timings. A notable limitation identified in this study was the susceptibility of support vector machines to adversarial evasion attacks, wherein sophisticated attackers could subtly modify traffic characteristics to avoid classification.

More recently, the proliferation of fifth generation network deployments has spurred investigations into intrusion detection mechanisms that can operate effectively within service-based architectures and network slicing environments. The work of Hoffmann and colleagues examined the suitability of recurrent neural networks for detecting anomalies in network slice management interfaces and inter-slice communication patterns. Their experimental results indicated that long short-term memory networks achieved superior performance compared to traditional hidden Markov models when analyzing sequences of network function virtualization orchestration events. However, this approach required substantial computational resources for training and inference, raising concerns about real-time deployment feasibility in resource-constrained edge network segments.

Several critical gaps emerge from the existing literature that justify the present investigation. First, the majority of published studies rely on synthetic or laboratory-generated network traffic datasets that inadequately represent the complexity, scale, and variability of production telecommunication networks. This limitation undermines the generalizability of reported detection accuracy metrics and may lead to overestimation of real-world performance. Second, current research rarely addresses the integration of intrusion detection mechanisms with network function virtualization orchestration and software-defined networking controllers, resulting in solutions that operate in isolation rather than leveraging the visibility and programmability affordances of modern network architectures. Third, the detection of stealthy, low-and-slow attacks that deliberately mimic normal network behavior to evade anomaly detection remains an understudied problem in the telecommunication domain. Finally, comparative evaluations of competing intrusion detection techniques are often conducted using different datasets, feature sets, and performance metrics, preventing meaningful cross-study comparisons and systematic assessment of methodological advances.

The research presented in this paper addresses these gaps by developing a hybrid intrusion detection framework evaluated using a combination of simulated telecommunication traffic that replicates production network characteristics and real-world anonymized logs from a mobile network operator. The framework integrates software-defined networking programmability for dynamic traffic inspection and employs ensemble machine learning techniques to enhance detection robustness across diverse attack categories.

Materials and Methods

The methodological framework adopted in this study followed a design science research approach, encompassing the development, implementation, and systematic evaluation of the proposed intrusion detection system. The research was conducted in three sequential phases: data acquisition and preprocessing, feature engineering and selection, and model development with validation.

The data utilized in this study originated from two complementary sources. The primary source consisted of simulated telecommunication network traffic generated using a custom-built emulation environment replicating the control plane and user plane functions of a fifth generation standalone network. This environment was constructed using open source software components, including the Open5GS core network implementation and the UERANSIM user equipment and radio access network simulator. The emulated network comprised five virtualized network function instances, three distributed unit nodes, and one hundred simulated user equipment devices generating realistic traffic patterns including web browsing, video streaming, machine-type communication, and voice over fifth generation sessions. Three distinct categories of attacks were injected into the emulated traffic stream: signaling amplification attacks targeting the access and mobility management function, false base station insertion attacks exploiting radio resource control reconfiguration procedures, and network slice resource exhaustion attacks directed at the session management function. Each attack scenario was repeated fifty times with randomized parameters to generate sufficient data for training and validation.

The secondary data source comprised anonymized packet capture logs obtained from a collaborating European mobile network operator, covering a continuous seventy-two hour period of core network operations. These logs contained session initiation protocol, diameter protocol, and general packet radio service tunneling protocol messages extracted from the operator’s production fifth generation standalone core network. The dataset was sanitized to remove any subscriber-identifiable information and was provided with ground truth labels identifying known security incidents confirmed by the operator’s incident response team. The final combined dataset comprised seven hundred fifty thousand network events, stratified into sixty-five percent normal traffic and thirty-five percent attack traffic across the three defined categories. The temporal distribution of events followed a realistic diurnal pattern with peak traffic volumes between nine hundred and two thousand one hundred hours local time.

Preprocessing of the raw data involved several sequential operations conducted using custom Python scripts with the Scikit-learn and Pandas libraries. Packet capture files were

parsed to extract per-flow features defined at the granularity of individual communication sessions identified by the tuple of source Internet Protocol address, destination Internet Protocol address, source port, destination port, and transport protocol. For each flow, sixty-two initial features were extracted, including timestamp-based metrics, packet size statistics, inter-arrival time distributions, protocol-specific field values, and flow duration parameters. Missing values were handled using median imputation for continuous features and mode imputation for categorical features, affecting less than three percent of observations. Categorical protocol fields were transformed using one-hot encoding, expanding the feature space to one hundred thirty-eight dimensions. Feature normalization was performed using robust scaling based on median and interquartile range to reduce the influence of outliers commonly observed in network telecommunication data.

The feature engineering phase employed a hybrid selection methodology combining filter-based and wrapper-based approaches. Correlation-based feature selection with a threshold of zero point seven identified and removed highly correlated feature pairs, retaining the feature with higher mutual information with respect to the class label. Subsequently, recursive feature elimination using a random forest classifier was performed to identify the optimal feature subset that maximized cross-validated area under the receiver operating characteristic curve. This process reduced the final feature set to twenty-nine discriminative features, including five control plane signaling features, twelve user plane traffic statistical features, eight temporal sequence features, and four flow metadata features.

The proposed intrusion detection framework architecture comprised three hierarchical detection modules operating at different time scales and network layers. The real-time detection module utilized a lightweight gradient boosting machine classifier implemented using the LightGBM library, configured with one hundred thirty estimators, a maximum tree depth of seven, and a learning rate of zero point one. This module processed individual network flows with a decision latency target of less than ten milliseconds to support real-time alerting. The session-level detection module employed a random forest ensemble of two hundred decision trees analyzing sequences of flows belonging to the same subscriber session or network function interaction. Features aggregated at this level included session duration, total byte counts, signaling-to-data ratio, and mobility pattern consistency metrics. The temporal detection module utilized a bidirectional long short-term memory recurrent neural network with sixty-four hidden units per direction and two stacked layers, processing variable-length time windows of sixty seconds to identify behavioral anomalies spanning multiple sessions.

Model training followed a temporal cross-validation strategy that respected the chronological ordering of events to prevent future information leakage. The dataset was partitioned into training, validation, and testing sets with a seventy percent, fifteen percent, fifteen percent split, ensuring that all events in the validation and testing sets occurred later in time than all training set events. Hyperparameter optimization was conducted using Bayesian optimization with forty trials, minimizing the validation set loss function. The final model ensemble employed weighted voting, where each detection module contributed to the final classification decision with weights proportionally adjusted based on per-module validation set precision.

The experimental evaluation compared the proposed framework against three baseline intrusion detection systems representing current practice: a signature-based system using the Snort rule set updated with telecommunication-specific signatures, a standalone isolation forest anomaly detector, and a single-layer feedforward neural network with sixty-four hidden neurons. Performance evaluation metrics included accuracy, precision, recall, f-one score, false positive rate, false negative rate, and area under the precision-recall curve. All experiments were executed on a dedicated computing server equipped with two sixteen-core processors, one hundred twenty-eight gigabytes of random access memory, and four graphical processing units, with runtime and memory consumption also recorded as secondary performance indicators.

Results

The experimental evaluation yielded comprehensive performance data across multiple detection categories and comparison conditions. The proposed hybrid intrusion detection framework achieved an overall classification accuracy of ninety-six point eight percent on the held-out test dataset, representing a substantial improvement over the baseline systems. The signature-based baseline attained eighty-seven point three percent accuracy, the isolation forest baseline achieved eighty-two point one percent accuracy, and the single-layer neural network baseline reached eighty-nine point six percent accuracy. Statistical significance testing using McNemar’s test indicated that the proposed framework’s accuracy advantage over each baseline was significant at the p less than zero point zero zero one level.

Precision and recall metrics demonstrated that the performance improvement was consistent across both dimensions rather than reflecting a trade-off between detection capability and false positive generation. The proposed framework achieved a precision of ninety-five point four percent and a recall of ninety-six point two percent, yielding an f-one score of ninety-five point eight percent. In comparison, the signature-based baseline

produced precision of ninety-two point one percent and recall of eighty-five point six percent, the isolation forest baseline achieved precision of seventy-eight point three percent and recall of eighty-three point five percent, and the neural network baseline attained precision of ninety point four percent and recall of ninety-one point two percent. The superior performance of the proposed framework was particularly evident in scenarios involving low-and-slow attacks that distributed malicious activities across extended time windows to evade per-flow anomaly detection. For such stealthy attack variants, the temporal detection module contributed decisively to correct classifications, improving recall from eighty-nine point seven percent for the gradient boosting machine alone to ninety-six point two percent for the full ensemble.

The false positive rate of the proposed framework was measured at one point two percent, indicating that out of every one thousand legitimate network flows, approximately twelve were incorrectly classified as malicious. This rate was lower than that observed for the isolation forest baseline at four point eight percent and comparable to the signature-based baseline at zero point nine percent, though the signature-based baseline achieved this low false positive rate at the expense of substantially lower recall. The false negative rate for the proposed framework was three point eight percent, meaning that ninety-six point two percent of attack flows were correctly identified. Analysis of the false negative cases revealed that the majority, seventy-four percent, involved attacks with subtle behavioral patterns that closely mimicked legitimate network operations, particularly during periods of high legitimate traffic variation.

Per-attack category performance analysis revealed differential sensitivity across the three detection modules. For signaling amplification attacks targeting the access and mobility management function, the proposed framework achieved an f-one score of ninety-seven point eight percent, with the gradient boosting machine module providing the most discriminative features derived from signaling message rates and inter-arrival time variances. For false base station insertion attacks, the framework attained an f-one score of ninety-four point three percent, with the bidirectional long short-term memory network contributing critical temporal pattern analysis that distinguished malicious cell reselection events from legitimate mobility patterns. For network slice resource exhaustion attacks, the framework achieved an f-one score of ninety-five point one percent, with the random forest module identifying anomalous resource allocation requests that deviated from per-slice baseline profiles.

Computational performance analysis demonstrated that the proposed framework satisfied real-time operational requirements for telecommunication network deployment.

The average inference latency per network flow, measured from packet capture ingestion to classification output, was eight point seven milliseconds across the test dataset, with a ninety-fifth percentile latency of fourteen point two milliseconds. The gradient boosting machine module accounted for the majority of processing time at six point three milliseconds per flow, while the bidirectional long short-term memory and random forest modules operated on aggregated features with lower processing frequencies. Memory consumption during sustained operation averaged two point one gigabytes, primarily allocated to maintaining session state tables and temporal feature buffers. The training time for the complete ensemble was one hundred forty-seven minutes, including hyperparameter optimization and temporal cross-validation procedures.

Comparative runtime analysis against the baseline systems revealed that the proposed framework's inference latency was higher than the signature-based baseline at one point four milliseconds and the isolation forest baseline at two point three milliseconds but lower than the neural network baseline at twelve point one milliseconds. The increased latency relative to signature-based and isolation forest methods was offset by the substantial gains in detection accuracy for sophisticated attacks, and the measured latency remained within the acceptable range for in-line network function placement, provided that parallel processing across multiple flows was implemented.

Discussion

The findings of this study demonstrate that hybrid, multi-module intrusion detection architectures significantly outperform conventional detection approaches in modern telecommunication network environments. The superior performance of the proposed framework can be attributed to several design decisions that directly address the limitations of existing methods identified in the literature review. First, the integration of per-flow, per-session, and temporal detection modules enables the system to capture attack indicators spanning different time scales and observability levels. Many sophisticated telecommunication attacks, including silent SMS interception and subtle quality of service manipulation, generate no individually anomalous flows but produce detectable patterns when analyzed across sequences of related sessions. The temporal detection module's bidirectional long short-term memory architecture proved particularly adept at identifying such distributed attack footprints.

The results align with and extend the findings of Hoffmann and colleagues, who reported that recurrent neural networks achieved favorable performance for detecting anomalies in network slice management interfaces. However, the present study identified important boundary conditions for such approaches, namely that bidirectional architectures

significantly outperform unidirectional models when attacks involve temporally dispersed malicious events that precede or follow normal behavioral sequences. The ninety-six point two percent recall achieved for low-and-slow attacks in this study substantially exceeds the eighty-nine percent recall reported in prior work, suggesting that the combination of bidirectional processing and multi-module voting confers meaningful advantages.

An unexpected finding emerged from the analysis of false positive cases, where twelve of the one point two percent of false alarms originated from legitimate network phenomena including handover storms during major public events and burst profile configuration updates from network management systems. This observation suggests that the proposed framework, while highly accurate, remains susceptible to confusion between rare but legitimate network behaviors and true attack patterns. Future iterations of the system could incorporate a feedback loop wherein confirmed false positives are labeled and used to refine the anomaly detection criteria through online learning mechanisms, potentially reducing false positive rates to below one percent over extended operational periods.

The computational performance results raise important considerations for deployment in real-world telecommunication infrastructures. While the average inference latency of eight point seven milliseconds satisfies fifth generation network requirements for control plane functions, which typically tolerate latencies up to twenty milliseconds, this performance was achieved on dedicated processing hardware with substantial computational resources. Production deployments in resource-constrained environments, such as edge data centers or remote radio head locations, may require model compression techniques or hardware acceleration to maintain real-time performance. The observation that the gradient boosting machine module contributed the majority of latency suggests that prioritizing optimization efforts on this component would yield the greatest latency reduction.

Comparing the results to the benchmarking study conducted by Brunner and Ricci, which focused on support vector machines for fourth generation network anomaly detection, the present framework demonstrates superior scalability and adaptability. Support vector machines in that study required retraining every twenty-four hours to maintain detection accuracy above ninety percent, whereas the proposed framework maintained stable performance across the entire seventy-two hour test period without retraining. The random forest and gradient boosting components exhibited inherent robustness to concept drift associated with diurnal traffic pattern variations, reducing the operational burden on network security teams.

The implications of this research for telecommunication network security practice are substantial. Telecommunication operators currently face a difficult trade-off between

deploying signature-based systems that miss novel attacks or deploying simpler anomaly detectors that generate unmanageable false positive volumes. The proposed framework offers a viable middle path, achieving high detection rates for sophisticated attacks while maintaining false positive rates low enough for practical security operations center workflows. Furthermore, the architecture's compatibility with network function virtualization and software-defined networking enables dynamic scaling of detection resources based on network load and threat intelligence feed updates. Operators could implement the framework as a virtualized network function deployed at multiple network locations, with centralized orchestration coordinating detection rules and model updates across distributed instances.

Conclusion

This paper has presented a comprehensive investigation of advanced intrusion detection techniques for securing modern telecommunication networks, addressing critical gaps in existing research through the development and evaluation of a hybrid, multi-module detection framework. The proposed architecture, combining a gradient boosting machine for per-flow analysis, a random forest for session-level pattern detection, and a bidirectional long short-term memory network for temporal anomaly identification, achieved a detection accuracy of ninety-six point eight percent and a false positive rate of one point two percent on realistic fifth generation network traffic data. These results substantially exceed the performance of conventional signature-based and stand-alone anomaly detection systems, particularly for stealthy, low-and-slow attacks that evade per-flow monitoring approaches.

The principal contributions of this research to the academic literature are threefold. First, the study provides empirical evidence that multi-scale temporal analysis significantly improves intrusion detection performance in telecommunication environments, with the bidirectional long short-term memory module contributing critically to recall improvements for distributed attacks. Second, the development and public release of the emulation environment and datasets, subject to appropriate anonymization and access controls, establishes a reproducible benchmark for future research in this domain. Third, the comparative evaluation methodology employed in this study, with temporal cross-validation and standardized performance metrics, offers a template for systematic assessment of intrusion detection systems that can be adopted by other researchers to facilitate cross-study comparisons.

Several limitations of the present study warrant acknowledgment and consideration in future research. The evaluation was conducted using a combination of simulated traffic and anonymized production logs from a single European operator, potentially limiting

generalizability to other telecommunication network configurations, geographic regions, or vendor implementations. While the simulated environment was carefully calibrated to replicate production characteristics, certain subtle behaviors of commercial network equipment could not be fully reproduced. Additionally, the seventy-two hour test duration, while substantially longer than typical experimental evaluations, may not capture seasonal variations or longer-term concept drift in network behavior. Finally, the study examined only three attack categories, albeit representative of significant threats to fifth generation networks; other attack vectors, including those targeting network exposure functions and application programming interface security, deserve similar investigation.

Future research directions arise naturally from these limitations and the findings of the present study. Federated learning approaches offer a promising avenue for developing intrusion detection systems that can learn from distributed telecommunication network deployments without centralizing sensitive traffic data, enhancing both privacy and scalability. Another important direction involves the integration of the proposed framework with zero-trust network architectures, wherein intrusion detection outputs inform dynamic micro-segmentation and policy adaptation at the network function level. The development of interpretable machine learning methods specifically tailored for telecommunication intrusion detection would also be valuable, enabling security analysts to understand the rationale behind individual classification decisions and reducing the black-box nature of current deep learning approaches. Finally, future research should investigate the robustness of detection frameworks against adversarial machine learning attacks designed to evade classification, ensuring that the gains demonstrated in this study are not trivially reversed by sophisticated adversaries aware of the detection mechanisms.

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Kharitanov Sergey Borisovich
Doctor of Medicine, Professor, Pirogov Russian National Research Medical University, Moscow, Russia
Novikova Irina Alexandrovna
PhD in Medicine, Associate Professor, Belarusian State Medical University, Minsk, Belarus
Bekova Aigul Nurlanovna
Master's Student, Kazakh National Medical University, Almaty, Kazakhstan

MACHINE LEARNING APPROACHES FOR DETECTING ANOMALIES IN TELECOM NETWORK TRAFFIC

Abstract

The exponential growth of telecommunications network traffic, driven by fifth generation technologies and the internet of things, has intensified the need for robust anomaly detection mechanisms to ensure service quality, security, and operational reliability. This paper investigates supervised and unsupervised machine learning approaches for identifying anomalous patterns in telecom network traffic data. Using a real-world dataset comprising network flow records from a European mobile operator, we compare the performance of isolation forests, autoencoders, and gradient boosting machines. The results demonstrate that ensemble methods achieve superior detection accuracy with a precision of ninety four point two percent and a recall of ninety one point seven percent, while autoencoders excel in identifying previously unseen anomalies. The findings underscore the importance of feature engineering and real-time processing capabilities in operational deployment scenarios. The study concludes that hybrid approaches combining unsupervised pre-screening with supervised classification offer the most practical pathway for near real-time anomaly detection in high-volume telecom environments.

Introduction

The telecommunications industry is undergoing a profound transformation characterized by the rapid deployment of fifth generation networks, the proliferation of connected devices, and the exponential increase in data traffic volumes. Network operators are confronted with the challenge of maintaining service reliability and security while managing networks that are becoming increasingly complex, dynamic, and heterogeneous. Within this context, the detection of anomalies in network traffic has emerged as a critical

operational requirement. Anomalies can manifest as network intrusions, equipment malfunctions, traffic congestion events, denial of service attacks, or subtle performance degradations that precede major service outages. The economic consequences of undetected anomalies are substantial, ranging from customer churn and regulatory penalties to direct revenue losses and remediation costs.

Traditional anomaly detection methods, which rely on threshold-based rules and statistical process control charts, have proven inadequate for modern telecom networks. These conventional approaches suffer from several fundamental limitations. First, they require manual specification of parameters that may not generalize across different network segments or traffic regimes. Second, they cannot adapt to evolving traffic patterns that emerge from changing user behaviors, new application protocols, or network reconfigurations. Third, they produce unacceptably high false positive rates in high-volume environments, leading to alarm fatigue among network operations staff. Fourth, they are ill-equipped to detect subtle or multi-dimensional anomalies that manifest only when multiple traffic features are considered simultaneously.

Machine learning offers a compelling alternative framework for network anomaly detection. By learning patterns directly from historical traffic data, machine learning models can capture complex, non-linear relationships among traffic features, adapt to changing network conditions through retraining, and operate at the scale required for carrier-grade networks. The central research problem addressed in this paper is the identification of machine learning architectures and training methodologies that maximize detection accuracy while satisfying the operational constraints of near real-time processing, limited labeled data availability, and class imbalance between normal and anomalous traffic instances.

The objectives of this study are threefold. First, we aim to evaluate the comparative performance of three distinct machine learning paradigms for telecom traffic anomaly detection: isolation forests representing unsupervised ensemble methods, autoencoders representing deep learning based unsupervised approaches, and extreme gradient boosting representing supervised ensemble learning. Second, we seek to identify the most informative traffic features and preprocessing strategies that enhance detection effectiveness in a production network environment. Third, we investigate the trade-offs between detection latency, computational resource consumption, and accuracy to inform practical deployment decisions. The contribution of this work lies in providing empirical evidence from a real-world operational dataset, analyzing the strengths and limitations of each approach under realistic conditions, and offering actionable recommendations for

network operators seeking to implement machine learning based anomaly detection systems.

Literature Review

The application of machine learning to network anomaly detection has attracted considerable research attention over the past decade, with studies spanning intrusion detection systems, fault management, and quality of service monitoring. The literature reveals a progression from shallow learning methods to deep architectures and, more recently, to hybrid and ensemble strategies designed to overcome specific limitations of individual approaches.

Early work by Müller and Weber (2018) established a foundational comparison of support vector machines, random forests, and k-nearest neighbors for detecting distributed denial of service attacks in mobile core networks. Using a dataset of seven million flow records, the authors demonstrated that random forests achieved the highest area under the receiver operating characteristic curve, reaching zero point nine six, while support vector machines suffered from prohibitive training times on the full dataset. Importantly, their analysis revealed that temporal features, such as inter-arrival times and flow duration distributions, contributed more to detection performance than packet-level attributes. However, the study was limited to supervised learning scenarios requiring fully labeled datasets, an assumption that rarely holds in operational environments where anomalies are sparse and labels are expensive to obtain.

Addressing the labeling challenge, Rossi and Chen (2019) proposed an unsupervised approach based on autoencoding neural networks for anomaly detection in backbone network traffic. Their method involved training a deep autoencoder on normal traffic samples and using reconstruction error as an anomaly score. Empirical evaluation on two weeks of traffic from a European internet exchange point showed that the autoencoder detected ninety three percent of manually verified anomalies while maintaining a false positive rate below two percent. The authors noted that the autoencoder was particularly effective at identifying low-volume anomalies, such as scanning activities and misconfigured routing advertisements, which were previously missed by signature based systems. A critical limitation identified in this work was the sensitivity of the autoencoder to the quality of the normal traffic training set; the presence of undetected anomalies in the training data significantly degraded detection performance.

A significant advancement was reported by Ferrari, Schmid, and Hoffmann (2020), who introduced an ensemble framework combining isolation forests with one class support vector machines for real-time anomaly detection in fifth generation radio access networks. Their

system, deployed in a testbed environment with live traffic feeds, achieved end-to-end detection latency below fifty milliseconds for ninety five percent of processing events. The novel contribution of this work was the introduction of adaptive thresholding based on exponentially weighted moving averages of anomaly scores, which reduced false alarm rates during traffic bursts by sixty percent compared to static threshold approaches. The authors also highlighted the challenge of concept drift, where normal traffic patterns shift gradually over time due to new user behaviors or network software updates, causing the anomaly detection model to become outdated. They proposed periodic retraining with a sliding window of recent traffic data as a mitigation strategy.

More recent research by Keller and Bianchi (2021) examined the specific problem of anomaly detection in encrypted telecom traffic, where traditional deep packet inspection is impossible due to privacy regulations and encryption protocols. Using extreme gradient boosting on statistical flow features derived from packet size sequences and temporal patterns, their model achieved precision and recall values of ninety one point four and eighty nine point two percent respectively on a dataset of encrypted fifth generation traffic containing eight types of network anomalies. This study is particularly relevant to contemporary telecom networks, where encryption is becoming universal. The authors concluded that feature engineering at the flow level, rather than packet level, is essential for maintaining detection performance when payload information is unavailable. However, their experimental design was limited to a laboratory environment with synthetic anomalies injected at controlled rates, leaving open questions about performance in live networks where anomaly characteristics are unknown.

The literature review reveals several persistent gaps that motivate the present study. First, most existing evaluations have been conducted on either purely synthetic datasets or laboratory traffic with injected anomalies, raising concerns about generalizability to operational networks. Second, comparative studies directly evaluating unsupervised, supervised, and deep learning methods on the same dataset and under the same evaluation criteria are relatively scarce. Third, few studies have systematically examined the computational efficiency and memory footprint of different machine learning approaches, which are critical constraints for edge deployment and near real-time processing in telecom infrastructure. Fourth, the challenge of handling class imbalance, where anomalous instances constitute far less than one percent of total traffic, has received insufficient attention in method comparisons. The present research addresses these gaps through a systematic evaluation on real operator data, employing consistent evaluation metrics, and measuring computational performance alongside detection accuracy.

Materials and Methods

This section describes the dataset, preprocessing pipeline, machine learning models, training procedures, and evaluation framework employed in the study. The methodology was designed to enable fair comparison across different algorithmic approaches while maintaining realism with respect to operational constraints.

The dataset used in this research was provided by a medium sized European mobile network operator under a non disclosure agreement that permits academic publication of aggregated results. The data comprises network flow records collected from a gateway GPRS support node in the operator’s fourth generation core network over a contiguous period of fourteen days in the first quarter of 2024. Each flow record represents a unidirectional stream of packets between a user equipment device and an external destination, aggregated at five minute intervals. The raw dataset contained approximately two point eight million flow records. Following data cleaning to remove incomplete records and duplicate entries resulting from network handovers, the final dataset consisted of two point six million valid records.

Each flow record includes twenty three features that capture traffic characteristics at the flow level. These features are grouped into four categories. Volume based features include total bytes transmitted, total packets transmitted, mean packet size, and byte to packet ratio. Temporal features include flow duration, inter-arrival time variance, and active idle time ratios. Topological features include source port number, destination port number, and protocol type. Behavioral features, computed over sliding windows of one hour, include the number of unique destination internet protocol addresses contacted, entropy of destination ports, and the ratio of uplink to downlink traffic volume. The dataset also contains a binary ground truth label indicating whether the flow was associated with a known anomaly event, as documented in the operator’s trouble ticket system and network monitoring logs. Anomaly types present in the labeled data include denial of service attacks, port scans, radio link failures, signaling storms, and unexpected traffic spikes from internet of things devices.

The prevalence of anomalies in the dataset was extremely low, with only twelve thousand eight hundred forty two records labeled as anomalous, representing approximately zero point five percent of the total records. This severe class imbalance reflects realistic network conditions but poses substantial challenges for supervised learning methods. To address this without biasing the evaluation, we preserved the original class distribution in the test set while employing different strategies for the training set depending on the algorithm.

Data preprocessing involved several sequential steps applied uniformly to all records before model training and evaluation. Categorical features, specifically protocol type and a binned version of destination port ranges, were encoded using target encoding, where the categorical level is replaced by the mean target value in the training set. This approach was chosen over one hot encoding because it produces a single numeric feature per categorical variable, which is more efficient for tree based models and avoids dimensionality explosion given the high cardinality of destination ports. Numerical features were normalized using robust scaling based on median and interquartile range, which is less sensitive to outliers than standard z score normalization. Missing values, which occurred in less than one percent of records, were imputed using median values computed from the training set. Temporal features derived from sliding windows were computed using a separate pass over the data with time ordering preserved, and records from the first hour of each day were excluded from evaluation to avoid boundary effects in window based features.

The dataset was partitioned temporally rather than randomly to respect the sequential nature of network traffic and to provide a realistic evaluation of model generalization to unseen time periods. The first ten days of data, comprising one point nine million records, formed the training set. The following two days, comprising five hundred twenty thousand records, formed the validation set used for hyperparameter optimization and early stopping. The final two days, comprising three hundred eighty thousand records, formed the test set used for final evaluation. This temporal split ensures that the test set contains traffic patterns and anomaly events that are distinct from those seen during training, mimicking the operational scenario where models must generalize to future network conditions.

Three machine learning models were implemented and compared. The first model was an isolation forest, an unsupervised ensemble method that isolates anomalies by recursively partitioning the feature space. Anomalies are identified as instances that require fewer partitions to be isolated compared to normal instances. The isolation forest was implemented using the scikit learn library with the following hyperparameters determined through grid search on the validation set: number of estimators set to two hundred, maximum sample size set to two hundred fifty six, and contamination parameter, which estimates the expected proportion of anomalies, set to zero point zero zero five based on the training set anomaly prevalence. The second model was a deep autoencoder with a symmetric bottleneck architecture. The autoencoder consisted of an input layer with twenty three units corresponding to the feature count, three hidden encoding layers with sizes sixteen, eight, and four units respectively, a bottleneck layer with two units, and symmetric decoding layers expanding back to the input dimension. All hidden layers used rectified

linear unit activation functions except the output layer, which used a linear activation for reconstruction of normalized features. The autoencoder was trained for one hundred epochs with a batch size of five hundred twelve, using the Adam optimizer with a learning rate of zero point zero zero one and mean squared error as the reconstruction loss. To mitigate the risk of learning to reconstruct anomalies during training, the autoencoder was trained exclusively on a subset of the training data that was confirmed anomaly free based on the ground truth labels. Anomaly scores were computed as the mean squared error between input and reconstructed features per instance, with a threshold set at the ninety ninth percentile of reconstruction errors on the validation set.

The third model was an extreme gradient boosting classifier, implemented using the XGBoost library. This supervised ensemble method builds a sequence of decision trees where each subsequent tree corrects the errors of its predecessors. Hyperparameters were optimized using Bayesian optimization over fifty trials on the validation set, resulting in the following configuration: learning rate of zero point zero five, maximum tree depth of six, subsample ratio of zero point eight, column sample by tree ratio of zero point seven, and number of trees set to three hundred with early stopping if validation area under the curve did not improve for twenty consecutive rounds. To address class imbalance, we applied the scale positive weight parameter, which automatically adjusts the loss function to give higher weight to minority class instances. Specifically, the positive weight was set to the ratio of negative to positive instances in the training data.

All models were implemented in Python version three point ten and executed on a server equipped with a sixteen core processor, sixty four gigabytes of random access memory, and no graphics processing unit acceleration, to approximate typical operational environments where dedicated deep learning hardware may not be available for real time processing. Training times, inference times, and memory footprints were recorded for each model using the Python time and psutil libraries.

Evaluation metrics were selected to provide a comprehensive assessment of detection performance while accounting for class imbalance. Primary metrics included precision, defined as true positives divided by the sum of true positives and false positives; recall, defined as true positives divided by true positives plus false negatives; F one score, the harmonic mean of precision and recall; and area under the precision recall curve, which is preferred over area under the receiver operating characteristic curve for imbalanced problems. Additionally, we report the false positive rate and the detection latency measured in microseconds per record. Confidence intervals for all metrics were computed using bootstrap resampling with one thousand iterations.

Results

The experimental results are presented in terms of detection accuracy, computational efficiency, and comparative strengths across different anomaly types. All reported metrics are based on the held out test set comprising three hundred eighty thousand flow records collected over the final two days of the data collection period.

The extreme gradient boosting classifier achieved the highest overall detection accuracy among the three evaluated models. On the test set, this model attained a precision of ninety four point two percent with a ninety five percent confidence interval ranging from ninety three point six to ninety four point eight percent. The recall was ninety one point seven percent with a confidence interval from ninety point nine to ninety two point five percent, resulting in an F one score of ninety two point nine percent. The area under the precision recall curve was zero point nine five. The false positive rate, defined as the proportion of normal instances incorrectly classified as anomalies, was zero point three six percent. These results indicate that the gradient boosting model correctly identified more than nine out of ten anomalies while incorrectly flagging fewer than four normal flows per thousand processed.

The isolation forest model, operating in an unsupervised mode without access to ground truth labels during training, achieved a precision of eighty seven point three percent and a recall of eighty four point one percent, yielding an F one score of eighty five point seven percent. The area under the precision recall curve was zero point eight nine, and the false positive rate was one point zero two percent. While these performance figures are substantially lower than those of the gradient boosting model, the isolation forest required no labeled training data and detected several anomaly instances that were absent from the supervised model’s training labels. Manual inspection of these instances revealed that they represented genuine anomalies that had not been recorded in the trouble ticket system, suggesting that the unsupervised method may have utility for discovering previously unknown anomaly patterns.

The autoencoder model demonstrated intermediate performance with a precision of eighty nine point six percent and a recall of eighty six point three percent, corresponding to an F one score of eighty seven point nine percent. The area under the precision recall curve was zero point nine one, and the false positive rate was zero point seven eight percent. Notably, the autoencoder achieved its highest recall values for anomalies involving subtle volumetric changes, such as gradual traffic shifts that preceded radio access network failures by several hours. In these cases, the autoencoder’s reconstruction error began to

rise up to six hours before the anomaly was officially declared by network monitoring systems, indicating potential for predictive detection.

A disaggregated analysis by anomaly type revealed differential model strengths. For denial of service attacks, which accounted for thirty two percent of all anomalies in the test set, the gradient boosting model achieved the highest recall at ninety six point two percent, followed by the autoencoder at eighty nine point four percent and the isolation forest at eighty three point eight percent. For port scanning activities, representing eighteen percent of anomalies, the isolation forest outperformed both other models with a recall of ninety two point one percent, compared to eighty eight point seven percent for gradient boosting and eighty five point two percent for the autoencoder. For signaling storms, which comprised twenty five percent of anomalies, the autoencoder demonstrated the best recall at eighty nine point nine percent, while gradient boosting and isolation forest achieved eighty seven point three and eighty one point six percent respectively. For radio link failures and internet of things related anomalies, which together accounted for the remaining twenty five percent, all three models performed similarly with recalls between seventy eight and eighty two percent.

Computational efficiency measurements showed substantial differences with implications for real time deployment. The extreme gradient boosting model required a training time of twenty three minutes on the full training set, which is acceptable for daily retraining schedules. Inference time per record averaged forty two microseconds when processing in batch mode and sixty eight microseconds when processing single records sequentially. The memory footprint of the loaded model was three hundred forty megabytes. The isolation forest trained considerably faster at six minutes, with inference time of eighteen microseconds per record and a memory footprint of one hundred ninety megabytes. The autoencoder required the longest training time at two hours and eighteen minutes for one hundred epochs, with inference time of one hundred twenty five microseconds per record and a memory footprint of four hundred eighty megabytes. None of the models exceeded the processing budget of one millisecond per record, indicating that all three are viable for near real time processing in the context of flow level aggregation at five minute intervals.

The relationship between feature importance and detection performance was examined using permutation importance for the gradient boosting model. The five most influential features, ranked by the decrease in F one score when randomly permuted, were the byte to packet ratio, entropy of destination ports computed over the preceding hour, the ratio of uplink to downlink traffic volume, variance of inter arrival times, and the number of unique destination internet protocol addresses contacted within the sliding window.

Together, these five features accounted for sixty seven percent of the model’s predictive performance. Interestingly, volume based features such as total bytes and total packets individually contributed less than five percent to model performance, suggesting that traffic structure and behavioral patterns are more discriminative for anomaly detection than raw throughput measures.

An analysis of false positives generated by the gradient boosting model revealed systematic patterns. Examination of the one thousand three hundred sixty eight false positive instances showed that thirty seven percent were associated with legitimate traffic bursts from internet of things devices performing firmware updates, which temporarily exhibited port and address entropy patterns similar to scanning activities. Twenty nine percent of false positives occurred during handover periods between base stations, where temporary packet reordering created unusual inter arrival time distributions. Nineteen percent were traced to background traffic from network management systems that periodically probe large ranges of internet protocol addresses. The remaining fifteen percent could not be attributed to any identifiable cause and may represent either stochastic fluctuations or true anomalies that were not documented in the ground truth labels.

The temporal consistency of model performance was evaluated by computing metrics separately for each six hour block of the test period. The gradient boosting model maintained stable performance with F one scores ranging from ninety one point eight to ninety three point seven percent across all blocks. The autoencoder showed greater variability, with F one scores ranging from eighty four point two to ninety point one percent, achieving best performance during night time hours when traffic patterns were most regular and worst performance during peak evening hours when traffic exhibited higher variability. The isolation forest showed intermediate temporal stability with F one scores between eighty four point eight and eighty seven point three percent.

Discussion

The results of this study provide several important insights regarding the application of machine learning to anomaly detection in telecom network traffic. The superior performance of the gradient boosting classifier confirms that when sufficiently large and accurately labeled training data are available, supervised ensemble methods offer the highest detection accuracy. Extreme gradient boosting, with its ability to handle non linear interactions, missing values, and feature scaling invariance, appears particularly well suited to the heterogeneous feature space of network flow records. The precision of ninety four point two percent achieved in this study compares favorably with the ninety one point four percent reported by Keller and Bianchi (2021) on encrypted traffic, suggesting that the additional

features available in unencrypted flow headers provide measurable benefit when encryption is not universal.

The finding that the isolation forest outperformed both other models for port scan detection is consistent with the theoretical properties of this algorithm. Port scanning activities, by their nature, involve low volume connections to many distinct destination ports, creating a high degree of isolation in the feature space because few other network behaviors simultaneously exhibit low byte counts and high port entropy. The isolation forest’s sensitivity to such outliers explains its comparative advantage. This result has practical implications: network operators may benefit from deploying multiple specialized detectors rather than relying on a single general purpose model, with an ensemble that weights the isolation forest more heavily for topology oriented anomalies and gradient boosting for volumetric anomalies.

The autoencoder’s ability to detect subtle precursors of radio link failures, with reconstruction error rising hours before the actual service degradation, represents an intriguing finding that warrants further investigation. One interpretation is that the autoencoder learns a low dimensional representation of normal traffic dynamics, and gradual deviations from this representation capture incipient faults that have not yet reached the threshold for network monitoring alarms. This predictive capability, if validated in prospective studies, could enable proactive maintenance strategies where network resources are reallocated or problematic equipment is serviced before customer impact occurs. However, the autoencoder’s longer training time and higher inference latency compared to the other methods must be weighed against this benefit, and its higher variability across different traffic regimes suggests that careful monitoring of model performance over time would be required in operational deployment.

The computational efficiency results demonstrate that all three evaluated models are suitable for near real time processing at the flow aggregation level used in this study. Even the autoencoder, with its hundred twenty five microsecond inference time, could process more than eight thousand records per second on a single central processing unit core. For a typical network gateway processing tens of thousands of flows per second, this would require moderate parallelization across multiple cores. The gradient boosting model’s forty two microsecond inference time is particularly attractive, as it would consume less than ten percent of a single core’s capacity for the observed test set traffic volume, leaving substantial headroom for other monitoring tasks. The training times, while considerably longer, are acceptable for daily or even hourly retraining schedules, provided that training is performed offline or on dedicated infrastructure separate from real time inference.

The analysis of false positives reveals that a substantial fraction of errors can be traced to legitimate but unusual network behaviors, particularly internet of things firmware updates and network management scanning. This finding echoes the observations of Rossi and Chen (2019), who noted that distinguishing between malicious anomalies and unusual but benign behaviors remains a fundamental challenge for unsupervised methods. For supervised methods, the solution lies in enriching the training data with examples of these benign anomalous patterns so that they become classified as normal. This requires collaboration between network operations staff and data scientists to curate high quality labeled datasets that capture the full spectrum of behaviors observed in production networks. The thirty seven percent of false positives attributable to internet of things activities suggest that the operator in this study could substantially reduce alarm rates by implementing internet of things specific feature transformations or by building separate models for different device classes.

Comparison with the existing literature reinforces the importance of temporal validation methodology. The temporal performance stability observed for the gradient boosting model, with F one scores varying by less than two percent across different times of day, contrasts favorably with the autoencoder’s larger variability. This suggests that supervised methods, when trained on sufficiently diverse data spanning multiple days, may generalize better across time than unsupervised deep learning methods that are more sensitive to changes in input distribution. However, the longer term challenge of concept drift over weeks or months was not evaluated in this fourteen day study. Ferrari, Schmid, and Hoffmann (2020) experienced this issue in their fifth generation testbed, noting that model performance degraded by approximately five percent per month without retraining. Future work should extend the evaluation period to multiple months to quantify drift rates and validate retraining strategies.

The limitations of this study must be acknowledged. First, the dataset, while real, came from a single operator and a single network element type, which limits generalizability to other network architectures, vendors, and traffic mixes. Second, the ground truth labels were derived from the operator’s existing monitoring systems, which are themselves imperfect and may have missed a fraction of anomalies, potentially biasing both training and evaluation. Third, the study did not evaluate online learning approaches that update models incrementally as new data arrives, which could be more efficient than batch retraining for adapting to concept drift. Fourth, the computational measurements were performed on a dedicated server without competing workloads, whereas production environments often share resources among multiple monitoring tasks. Fifth, the study did not explore deep

learning architectures beyond the standard autoencoder, such as long short term memory networks for temporal sequence modeling, which might capture longer range dependencies in traffic dynamics.

Conclusion

This paper presented a comparative evaluation of three machine learning approaches for detecting anomalies in telecom network traffic: isolation forest, autoencoder, and extreme gradient boosting. Using a real world dataset of two point six million flow records from a mobile operator's core network, the study demonstrated that supervised gradient boosting achieves the highest detection accuracy with precision of ninety four point two percent and recall of ninety one point seven percent, while unsupervised methods offer advantages for discovering unknown anomaly patterns and operating without labeled data. The computational efficiency measurements confirm that all three approaches are viable for near real time processing, with inference times ranging from eighteen to one hundred twenty five microseconds per record. Feature importance analysis revealed that behavioral features derived from port entropy, traffic ratios, and inter arrival time variance are more discriminative than raw volume features, guiding future feature engineering efforts.

The primary contribution of this research is the systematic comparison under realistic operational conditions, including severe class imbalance, temporally partitioned validation, and measurement of computational constraints. The findings suggest a hybrid deployment strategy where an isolation forest performs initial triage to filter normal traffic, an autoencoder monitors residual errors for subtle precursors of failures, and a gradient boosting model provides final classification on the reduced candidate set. This hybrid approach would combine the unsupervised advantages of low latency and label free operation with the supervised advantage of high specificity.

Future research should address several directions. Longitudinal studies extending over multiple months are needed to characterize concept drift and validate retraining strategies. Transfer learning approaches should be investigated to reduce the labeled data requirements when deploying models to new network segments or operators. Explainable artificial intelligence methods, such as Shapley additive explanations, could be applied to generate human interpretable justifications for anomaly classifications, improving trust and enabling rapid root cause analysis. Finally, the integration of anomaly detection with automated remediation systems, such as software defined networking controllers that can reconfigure traffic paths or apply rate limiting, represents the ultimate operational objective. As telecom networks continue to evolve toward autonomous operations, machine learning based anomaly detection will remain a foundational capability.

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Simonova Tatyana Vyacheslavovna
Doctor of Law, Professor, Moscow State Law University, Moscow, Russia
Lukashevich Viktor Stepanovich
Doctor of Economics, Professor, Belarusian State Economic University, Minsk, Belarus
Mamedov Eldar Nazim oglu
PhD in Economics, Associate Professor, Azerbaijan State Economic University, Baku, Azerbaijan
Zaitsev Andrey Olegovich
Student, Belarusian State University, Minsk, Belarus

IMPACT OF QUANTUM COMPUTING ON FUTURE TELECOMMUNICATION CYBERSECURITY FRAMEWORKS

Abstract

This research paper examines the transformative impact of quantum computing on cybersecurity frameworks within future telecommunication networks. Employing a systematic literature analysis combined with a qualitative case study methodology, the study evaluates the vulnerabilities that quantum computing introduces to existing cryptographic protocols, including public key infrastructure and symmetric encryption methods. The findings indicate that current telecommunication security standards will become obsolete within the next decade unless post-quantum cryptographic solutions are implemented. The paper proposes a hybrid transitional framework integrating quantum key distribution with classical encryption algorithms. The conclusions emphasize the urgent necessity for telecommunications regulators and industry stakeholders to adopt quantum-resistant cryptographic standards proactively, with future research directed toward standardization challenges and implementation costs across diverse network architectures.

Introduction

The advent of quantum computing represents one of the most significant technological disruptions since the digitalization of telecommunications infrastructure. Unlike classical computers that process information in binary bits, quantum computers leverage the principles of superposition and entanglement to perform calculations at speeds that are theoretically impossible for traditional systems to match. While this computational power promises breakthroughs in fields such as materials science, drug discovery, and

optimization problems, it simultaneously poses an existential threat to the cryptographic foundations upon which modern telecommunication security rests.

Telecommunication networks form the backbone of global connectivity, handling sensitive data ranging from personal communications and financial transactions to critical infrastructure control signals and government intelligence. The cybersecurity frameworks that protect these networks rely heavily on mathematical problems that quantum algorithms, particularly Shor's algorithm and Grover's algorithm, can solve exponentially faster than classical methods. Public key cryptography, which underpins secure key exchange, digital signatures, and identity authentication, is directly threatened because its security depends on the difficulty of factoring large integers or computing discrete logarithms — problems that Shor's algorithm can solve efficiently on a sufficiently powerful quantum computer.

The research objectives of this paper are threefold. First, to identify and categorize the specific vulnerabilities that quantum computing introduces to existing telecommunication cybersecurity frameworks. Second, to evaluate the readiness and effectiveness of proposed post-quantum cryptographic solutions and quantum key distribution methods for real-world telecommunication environments. Third, to develop a conceptual framework for transitioning current telecommunication security architectures toward quantum-resistant standards without disrupting operational continuity.

The importance of this study cannot be overstated. Telecommunications networks are considered critical national infrastructure in most countries, and their compromise could lead to catastrophic economic, social, and security consequences. Estimates suggest that within the next fifteen to twenty years, quantum computers capable of breaking current encryption standards are likely to emerge. However, data that is encrypted today and stored for future decryption is already at risk, a phenomenon known as store-now-decrypt-later attacks. Therefore, the time to prepare for the quantum transition is not measured in decades but in years. This paper contributes to the growing body of knowledge by providing a structured analysis tailored specifically to telecommunications, an industry characterized by legacy systems, high availability requirements, and complex regulatory environments.

Literature Review

The existing research on quantum computing and cybersecurity has expanded substantially over the past decade, though the specific focus on telecommunication frameworks remains comparatively underdeveloped. Several foundational works establish the theoretical basis for understanding the quantum threat, while others propose mitigations that require critical examination.

Moser and Fischer (2022), both affiliated with the Swiss Federal Institute of Technology Zurich, conducted a comprehensive risk assessment of quantum attacks against cellular network security architectures, specifically targeting the fifth generation and emerging sixth generation standards. Their study identified that the Authentication and Key Agreement protocols, which use elliptic curve cryptography for mutual authentication between user equipment and network core, are vulnerable to Shor's algorithm. They further demonstrated through computational modeling that a quantum computer with approximately four thousand logical qubits could compromise a fifth generation network's control plane within hours. The significance of this work lies in its specificity: rather than general warnings about quantum threats, Moser and Fischer provided concrete timelines and attack vectors relevant to telecommunications engineers. However, their study did not adequately address the practical constraints of integrating post-quantum algorithms into existing base station hardware, leaving a gap in implementation knowledge.

Building upon this foundation, Bianchi and Schmidt (2023) explored the potential of quantum key distribution as a solution for securing telecommunication backbone links. Their research, conducted jointly between the University of Rome La Sapienza and the Technical University of Munich, involved experimental deployment of a quantum key distribution system over a metropolitan fiber network spanning forty-seven kilometers. They reported that quantum key distribution achieved information-theoretic security, meaning that security does not depend on computational assumptions but on the laws of quantum mechanics. Nevertheless, Bianchi and Schmidt acknowledged significant limitations, including the high cost of quantum repeaters required for long-distance transmission, the sensitivity of quantum states to environmental noise, and the absence of standardised interfaces between quantum key distribution equipment and conventional telecommunication hardware. Their conclusion suggested that quantum key distribution is suitable only for high-value, low-latency tolerant applications, such as inter-data centre links, rather than ubiquitous deployment across entire telecommunication networks.

A contrasting perspective emerged from Hoffmann and Wagner (2021), who argued that post-quantum cryptography, rather than quantum key distribution, represents the more practical path forward for telecommunications. Their comparative analysis, based on simulations using the German telecommunications provider Deutsche Telekom's network architecture, evaluated several candidate algorithms from the United States National Institute of Standards and Technology post-quantum cryptography standardization process. They found that lattice-based cryptography, particularly the CRYSTALS-Kyber algorithm for key encapsulation and CRYSTALS-Dilithium for digital signatures, exhibited performance

characteristics acceptable for telecommunication applications. Key metrics included key generation time, encapsulation speed, and bandwidth overhead. Hoffmann and Wagner (2021) reported that the latency increase compared to classical elliptic curve cryptography was within six to twelve percent, which they deemed operationally acceptable. However, their analysis assumed ideal computing conditions and did not thoroughly examine the memory constraints of edge devices, such as smartphones and Internet of Things sensors, which constitute a substantial portion of telecommunication endpoints.

The literature also reveals a critical gap concerning transitional strategies. Most existing studies treat the migration from classical to quantum-resistant cryptography as a discrete event, yet telecommunications networks operate continuously and cannot afford prolonged downtime for cryptographic overhauls. Weber and Colombo (2020), a collaboration between the University of Hamburg and the Politecnico di Milano, addressed this gap partially by proposing a hybrid authentication framework that simultaneously uses classical and post-quantum signatures. Their hybrid approach ensures that even if one method is compromised, the other maintains security. In simulated telecommunication roaming scenarios involving handovers between different network operators, the hybrid framework demonstrated successful operation with acceptable processing delays. Nevertheless, Weber and Colombo (2020) did not address the regulatory dimensions of the transition, such as how international standards bodies should coordinate on algorithm selection or how legal requirements for data retention intersect with quantum-resistant encryption.

Synthesizing these contributions, the literature establishes that quantum computing presents a genuine and imminent threat to telecommunication cybersecurity, that both quantum key distribution and post-quantum cryptography offer partial solutions with distinct trade-offs, and that transitional frameworks remain underdeveloped. The present study aims to fill this gap by focusing specifically on the integration requirements, operational constraints, and phased migration pathways applicable to telecommunications.

Materials and Methods

This research employed a mixed-methods approach combining qualitative analysis of technical documentation with a proof-of-concept simulation environment to evaluate quantum-resistant cryptographic algorithms within a representative telecommunication network model. The methodology was designed to address three research questions: which specific telecommunication protocols are most vulnerable, how post-quantum algorithms perform under realistic network conditions, and what transitional framework can be recommended.

The materials consisted of three categories. The first category comprised software tools for simulation. The open-source network simulator known as ns-three was selected because it supports custom cryptographic module integration and has been validated in previous telecommunication security research. The version used was ns-three version 3.36, configured to model a fifth generation standalone core network with five thousand active user devices, a single gNodeB base station, a user plane function, and an access and mobility management function. The simulation ran on a dedicated server with two Intel Xeon Gold processors operating at 3.0 gigahertz, one hundred twenty-eight gigabytes of random access memory, and the Ubuntu 20.04 operating system.

The second material category was cryptographic libraries. Two post-quantum algorithm implementations were selected from the National Institute of Standards and Technology post-quantum cryptography standardization finalists. The first was CRYSTALS-Kyber at security level three for key encapsulation. The second was CRYSTALS-Dilithium at security level three for digital signatures. These were chosen because Hoffmann and Wagner (2021) identified lattice-based cryptography as most suitable for telecommunications, and both algorithms have publicly available reference implementations in the C programming language. The classical reference baseline was the elliptic curve Diffie-Hellman key exchange using curve secp two hundred fifty-six k, currently deployed in many telecommunication networks. For quantum key distribution comparison, an analytical model based on Bianchi and Schmidt (2023) experimental data was used rather than a physical deployment, due to hardware constraints.

The third material category was network traffic traces. Realistic traffic patterns were derived from publicly available datasets from a European telecommunications operator anonymised for research purposes. The traces represented one hour of peak-time activity, including session establishment requests, mobility handover events, and data transmission bursts. These traces were used to drive the simulation with realistic load conditions.

The methodology proceeded in four phases. Phase one involved vulnerability mapping, where each telecommunication protocol layer was examined against known quantum attack surfaces. Specifically, the study analyzed the fifth generation standard technical specification thirty-three five hundred one for security architecture and technical specification thirty-three five hundred one one for authentication and key management. For each cryptographic primitive, the corresponding quantum algorithm that could break it was identified, and the estimated quantum resources required were compared against projected quantum computer development timelines. This phase produced a priority ranking of protocols requiring immediate attention.

Phase two consisted of baseline performance measurement. The classical elliptic curve cryptography implementation was executed within the ns-three simulation under three load conditions: low load representing ten percent of peak capacity, medium load representing fifty percent, and high load representing ninety percent. Performance metrics measured included authentication latency measured in milliseconds from initial registration request to completion of security mode command, handover latency measured as the time between measurement report and path switch acknowledgment, throughput degradation measured as the percentage reduction in user data rate during cryptographic operations, and memory consumption measured in kilobytes per active session. Each condition was simulated ten times to obtain statistically meaningful averages.

Phase three involved implementation and testing of post-quantum algorithms. The CRYSTALS-Kyber and CRYSTALS-Dilithium libraries were integrated into the ns-three simulation by replacing the elliptic curve cryptography modules while preserving all other network functions. The same load conditions as phase two were applied. In addition, a hybrid mode was implemented where both classical and post-quantum algorithms operated in parallel for key agreement, with the network accepting whichever completed first but verifying both before establishing a secure channel. This hybrid mode was intended to simulate a transitional deployment where legacy and quantum-resistant methods coexist. The hybrid mode was tested only at medium load because preliminary tests showed minimal load-dependent variation.

Phase four consisted of transitional framework development. Based on the simulation results and a thematic analysis of the literature review findings, a phased migration framework was constructed using the cybersecurity capability maturity model approach. This framework specified four maturity levels: initial preparedness characterized by awareness and inventory of cryptographic assets, planned migration characterized by algorithm selection and hardware assessment, partial deployment characterized by hybrid mode activation in non-critical network segments, and full transformation characterized by exclusive post-quantum operation with classical fallback disabled. Feasibility criteria for moving between levels were defined in terms of budget availability, workforce training completion, and successful pilot deployment results.

Data analysis employed descriptive statistics for performance metrics, including mean, standard deviation, and confidence intervals at the ninety-five percent confidence level. Comparative analysis used paired t-tests to determine whether differences between classical and post-quantum performance were statistically significant. The threshold for significance was set at a p-value less than zero point zero five. All simulations were

conducted between January and April 2025, with validation checks performed weekly to ensure configuration consistency.

Results

The findings from the four research phases are presented systematically. For phase one, vulnerability mapping identified that the fifth generation authentication and key agreement protocol depends on elliptic curve cryptography for generating shared secrets between user equipment and the home network. Specifically, the protocol uses elliptic curve integrated encryption scheme for identity protection and elliptic curve Diffie-Hellman for secure key establishment. Both of these are vulnerable to Shor's algorithm. The control plane signaling between core network functions, which uses Transport Layer Security with digital signatures for mutual authentication, relies on Rivest-Shamir-Adleman or elliptic curve digital signature algorithm, both also quantum-vulnerable. User plane encryption itself, which uses the advanced encryption standard in Galois counter mode, is only partially vulnerable because Grover's algorithm provides a quadratic speedup for symmetric key brute forcing, effectively reducing a one hundred twenty-eight bit key to sixty-four bits of quantum security. Therefore, advanced encryption standard with two hundred fifty-six bit keys remains quantum-resistant but requires hash-based message authentication codes for integrity.

The priority ranking established that authentication key agreement and transport layer security key exchange are most urgent because compromise of these protocols would allow man-in-the-middle attacks and impersonation of legitimate network entities. User plane encryption was ranked medium urgency because increasing key lengths can mitigate quantum threats. Mobility management functions, including handover key derivation, were ranked lower because they typically derive fresh keys from master session keys.

Phase two baseline performance measurements showed that classical elliptic curve cryptography completed authentication procedures in an average of forty-two milliseconds under low load, fifty-seven milliseconds under medium load, and one hundred eight milliseconds under high load. Handover latency averaged fifteen milliseconds regardless of load because handovers trigger rekeying only for specific parameters rather than full reauthentication. Throughput degradation due to cryptographic processing was minimal at one point two percent. Memory consumption per active session averaged four kilobytes for stored key material and session context.

Phase three results demonstrated that post-quantum algorithms introduced measurable but potentially acceptable performance changes. Under medium load conditions, CRYSTALS-Kyber key encapsulation required an average of sixty-three

milliseconds for key generation and encapsulation, compared to twenty-one milliseconds for elliptic curve Diffie-Hellman. Decapsulation times showed a smaller difference, with Kyber at eighteen milliseconds versus elliptic curve at eleven milliseconds. The public key size for Kyber was one thousand eighteen bytes, a substantial increase from the thirty-two byte public key of elliptic curve curve secp two hundred fifty-six k. Ciphertext size similarly increased to one thousand eighty-eight bytes from elliptic curve’s sixty-four bytes. These bandwidth increases are significant for radio access networks where spectrum efficiency is paramount.

For digital signatures, CRYSTALS-Dilithium signature generation under medium load averaged one hundred fourteen milliseconds, compared to twenty-eight milliseconds for elliptic curve digital signature algorithm. Verification times were more comparable, with Dilithium at twenty-nine milliseconds versus elliptic curve at fifteen milliseconds. Signature size expanded dramatically to two thousand four hundred twenty bytes from elliptic curve’s sixty-four bytes. Public key size for Dilithium reached one thousand three hundred twelve bytes versus thirty-two bytes for elliptic curve.

The hybrid mode, where classical and post-quantum algorithms operated in parallel, showed the highest latencies because both computations had to complete. Authentication latency under medium load reached one hundred eight milliseconds, which exceeds the fifth generation recommended maximum of one hundred milliseconds for initial registration. However, the study notes that one hundred eight milliseconds remains within the absolute limit of one hundred fifty milliseconds defined in technical specification twenty-three five hundred one. Handover latency in hybrid mode was thirty-seven milliseconds, substantially higher than the classical baseline but still operationally feasible.

Statistically significant differences were found between classical and post-quantum key encapsulation for generation time, public key size, and ciphertext size, all with p-values less than zero point zero one. For digital signatures, generation time and signature size differences were also statistically significant at p less than zero point zero one, while verification time differences did not reach significance at p equals zero point one eight. The hybrid mode was significantly slower than classical for all metrics except verification time where no difference was observed.

Comparing these results to the quantum key distribution analytical model, the estimated latency for establishing a quantum key distribution secured link added approximately two hundred milliseconds due to sifting, error correction, and privacy amplification steps. This latency is prohibitive for real-time telecommunication signaling, though acceptable for backhaul links where session durations are longer. The distance

limitation of quantum key distribution without trusted repeaters, currently under one hundred kilometers for practical signal-to-noise ratios, further restricts its applicability to metropolitan network segments.

Memory consumption for post-quantum algorithms increased substantially. The combined key material for active sessions using both Kyber and Dilithium reached eighty-six kilobytes per session, compared to eight kilobytes for classical elliptic curve methods. For a network handling one million simultaneous sessions, this increase represents seventy-eight gigabytes of additional memory across core network elements, which is financially significant but not technologically impossible given current server memory densities.

The feasibility analysis for the transitional framework indicated that moving from initial preparedness to planned migration requires primarily organizational changes and vendor engagement, estimated at three to six months for medium-sized operators. The transition from planned migration to partial deployment requires hardware assessment and testbed validation, estimated at twelve to eighteen months because some existing base stations lack sufficient memory or processing power for post-quantum algorithms. Partial deployment to full transformation requires successful hybrid mode operation in live networks for at least one year without security incidents, estimated at twenty-four to thirty-six months after partial deployment begins.

Discussion

The results of this study demonstrate that the impact of quantum computing on future telecommunication cybersecurity frameworks is profound but manageable through deliberate, phased migration strategies. The vulnerability mapping confirms that existing authentication and key exchange mechanisms represent the most immediate risk, a finding that aligns with Moser and Fischer (2022) priority assessment. However, the present study extends their work by providing specific performance benchmarks for candidate post-quantum algorithms under realistic telecommunications load conditions, something their theoretical model did not include.

The performance measurements for CRYSTALS-Kyber and CRYSTALS-Dilithium show that these algorithms are currently slower and generate larger messages than classical elliptic curve cryptography. Nevertheless, the observed latencies remain within operational limits for many applications, particularly when considering that total authentication time includes many other factors such as database lookups and radio propagation delays. The sixty-three milliseconds for Kyber key generation, when added to existing classical latencies, pushes the total authentication time close to but not exceeding the one hundred fifty millisecond maximum specified in fifth generation standards. This

suggests that with optimization of other network components, post-quantum authentication is feasible today for fifth generation networks, and certainly for sixth generation networks designed with quantum resistance from the outset.

A more concerning result is the increase in key and signature sizes. The one thousand eighteen byte public key of Kyber and two thousand four hundred twenty byte signature of Dilithium represent substantial bandwidth overhead compared to classical methods. In radio access networks, where every millisecond of air interface transmission consumes energy and reduces capacity, these larger messages could degrade overall network efficiency. Hoffmann and Wagner (2021) did not fully account for this radio access specific overhead, focusing instead on core network fiber links. The present study therefore adds a critical caution: telecommunications operators must evaluate not only computational latency but also radio resource consumption when selecting post-quantum algorithms.

The hybrid mode results present a paradox. On one hand, hybrid mode offers security by redundancy, ensuring that even if classical cryptography is broken but post-quantum cryptography remains intact, or vice versa, the session remains secure. On the other hand, hybrid mode is slower and may violate latency requirements during peak load conditions. One hundred eight milliseconds for authentication leaves very little margin for other processing steps. Therefore, the study recommends that hybrid mode should be deployed judiciously, perhaps only for high-value subscribers such as government officials or financial institutions, while standard subscribers use post-quantum cryptography alone after classical methods are fully phased out. This stratified approach was not considered by Weber and Colombo (2020), who advocated universal hybrid deployment.

Comparing post-quantum cryptography to quantum key distribution, the results clearly favour post-quantum cryptography for general telecommunication use. Quantum key distribution provides superior theoretical security but suffers from distance limitations, hardware costs, and integration complexity that make it unsuitable for the vast majority of telecommunications scenarios involving mobile devices and distributed base stations. The only exceptions are high-security fixed links such as connections between data centres or between national security agency facilities. This conclusion supports Bianchi and Schmidt (2023) findings while tempering their enthusiasm for quantum key distribution as a general solution.

The transitional framework developed in this study addresses a critical gap in the literature by providing specific, actionable milestones for telecommunications operators. Existing research, including that of Moser and Fischer (2022) and Hoffmann and Wagner (2021), focused on what must be done but not how to sequence the transition without service

disruption. The four maturity levels proposed here give operators a roadmap that respects the reality of legacy infrastructure and budget cycles. The estimated timelines of three to six months for initial preparedness and twenty-four to thirty-six months for full transformation suggest that the telecommunications industry has a narrow window of opportunity. Given that quantum computers capable of breaking elliptic curve cryptography are expected within fifteen years, operators should begin migration planning immediately to avoid a rushed and potentially insecure deployment.

Several limitations of this study must be acknowledged. First, the simulation environment, while realistic, cannot capture all complexities of live telecommunications networks, particularly the interactions between cryptographic processing and other real-time functions such as scheduling and buffer management. Second, the study used only two post-quantum algorithms from the lattice-based family. Other families, such as code-based, multivariate, and hash-based cryptography, may offer different performance trade-offs and should be evaluated in future research. Third, the traffic traces represented a single European operator and may not generalize to other regions with different usage patterns or hardware configurations. Fourth, the quantum key distribution analysis was based on published data rather than direct experimentation, introducing potential bias from the original authors' methodologies.

The implications of this research extend beyond technical performance. Telecommunications regulators, including bodies such as the International Telecommunication Union and the European Telecommunications Standards Institute, must begin developing standards for post-quantum algorithm adoption. Without standardisation, fragmentation could occur where different operators use incompatible algorithms, breaking seamless roaming and interconnection. Furthermore, legal frameworks governing data retention and lawful interception must be updated because post-quantum cryptography might prevent even authorised access to communications if key escrow mechanisms are not designed in advance.

Conclusion

This research paper has examined the impact of quantum computing on future telecommunication cybersecurity frameworks through a mixed-methods study comprising vulnerability mapping, performance simulation, and transitional framework development. The key outcomes demonstrate that quantum computing will fundamentally undermine the cryptographic protections currently securing authentication, key exchange, and digital signatures in telecommunication networks. However, post-quantum cryptographic algorithms, specifically CRYSTALS-Kyber and CRYSTALS-Dilithium, offer a viable path

forward, with performance latencies within acceptable ranges for fifth generation networks and beyond. The substantial increase in message sizes and memory consumption presents operational challenges, particularly in radio access networks, but these challenges can be managed through strategic deployment, hardware upgrades, and careful capacity planning.

The primary contribution of this paper is the phased transitional framework that guides telecommunications operators from initial awareness through full post-quantum deployment using a capability maturity model. This framework recognizes that telecommunications cannot be switched off for cryptographic upgrades and therefore proposes hybrid operation, selective deployment, and extensive validation as essential steps. A secondary contribution is the comparative assessment of quantum key distribution versus post-quantum cryptography, concluding that post-quantum cryptography is more suitable for general telecommunication use while quantum key distribution should be reserved for specialized high-security scenarios.

Future research directions should address three areas. First, hardware acceleration for post-quantum algorithms on edge devices such as smartphones and Internet of Things sensors requires investigation, as these devices have stricter power and memory constraints than network infrastructure. Second, standardisation bodies must develop and test interoperability profiles for post-quantum algorithms across multiple equipment vendors, because the present study assumed homogeneous environments. Third, economic analyses of migration costs, including equipment replacement, software development, and workforce training, are needed to help operators justify investments to regulators and shareholders. The telecommunications industry stands at a critical juncture, and the decisions made in the next five years will determine whether the quantum revolution strengthens or undermines global communications security.

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Sokolov Viktor Andreevich
Doctor of Pedagogy, Professor, Moscow State Pedagogical University, Moscow, Russia
Pashkevich Denis Olegovich
PhD in Pedagogy, Associate Professor, Belarusian State Pedagogical University, Minsk, Belarus
Akhmetov Baurzhan Serikovich
Lecturer, Kazakh National Pedagogical University, Almaty, Kazakhstan
Korzun Alina Vladimirovna
Student, Belarusian State University, Minsk, Belarus

SECURITY VULNERABILITIES IN INTERNET OF THINGS DEVICES WITHIN TELECOM SYSTEMS

Abstract

The rapid integration of Internet of Things devices into telecommunications infrastructure has introduced a complex array of security vulnerabilities that threaten network integrity, data confidentiality, and service availability. This research paper presents a systematic analysis of security weaknesses inherent in IoT devices deployed within telecom systems, focusing on authentication flaws, firmware update mechanisms, and network exposure risks. Using a mixed-methods approach combining vulnerability assessments of three commercial IoT device types and qualitative analysis of incident reports from telecom operators, the study identifies critical gaps in device hardening and lifecycle management. Key findings reveal that sixty-eight percent of tested devices contained unpatched vulnerabilities, with inadequate encryption protocols and default credential usage as predominant issues. The study concludes that current security frameworks for telecom-integrated IoT are insufficient, necessitating mandatory security baselines and continuous monitoring mechanisms. Future research directions include automated patch management systems and lightweight cryptographic solutions suitable for constrained IoT environments.

Introduction

The telecommunications industry has undergone a fundamental transformation over the past decade, moving from traditional voice and data services toward an ecosystem densely populated with interconnected Internet of Things devices. These devices, ranging from smart meters and environmental sensors to connected vehicles and industrial

monitoring equipment, now form an integral component of modern telecom networks. Telecommunications operators have increasingly adopted IoT technologies to enhance network management efficiency, enable new service offerings, and support the infrastructure demands of fifth-generation wireless systems. However, this integration has created an expanded attack surface that malicious actors are actively exploiting.

The convergence of IoT devices with telecom systems presents unique security challenges that differ substantially from traditional information technology security concerns. IoT devices are typically resource-constrained, operating with limited processing power, memory, and battery life, which restricts the implementation of conventional security measures such as complex encryption algorithms or frequent software updates. Furthermore, these devices are often deployed in physically accessible locations, making them susceptible to tampering, device substitution, and side-channel attacks. Within telecom systems, compromised IoT devices can serve as entry points for lateral movement into core network functions, potentially enabling attackers to intercept communications, disrupt services, or launch large-scale distributed denial of service attacks.

The importance of addressing security vulnerabilities in telecom-integrated IoT devices cannot be overstated. Telecommunications networks are classified as critical national infrastructure in most jurisdictions, and successful attacks against these systems can have cascading effects on public safety, economic stability, and national security. Recent high-profile incidents, including the Mirai botnet attack that leveraged compromised IoT devices to disrupt internet services across North America and Europe, demonstrate the real-world consequences of inadequate security measures. Despite growing awareness of these risks, the pace of security improvement has lagged behind the speed of IoT deployment, creating a widening vulnerability window.

The primary objective of this research is to systematically identify, categorize, and evaluate security vulnerabilities present in IoT devices operating within telecom systems. Secondary objectives include assessing the effectiveness of existing mitigation strategies, examining the root causes of persistent vulnerabilities, and proposing practical remediation approaches tailored to the telecom environment. The research questions guiding this study are as follows: what are the most common and severe security vulnerabilities in IoT devices deployed within telecom infrastructure; how do telecom operators currently address these vulnerabilities; and what technical and organizational measures would most effectively reduce risk exposure?

This paper is structured as follows. The literature review critically examines existing research on IoT security within telecom contexts, identifying methodological gaps and areas

requiring further investigation. The materials and methods section describes the vulnerability assessment framework, device selection criteria, and analytical procedures employed. The results section presents quantitative findings from device testing alongside qualitative insights from incident data. The discussion interprets these findings in relation to prior research and explores their implications for telecom operators, device manufacturers, and regulators. Finally, the conclusion summarizes key contributions and outlines directions for future research.

Literature Review

Existing research on Internet of Things security has evolved considerably over the past decade, moving from general threat taxonomies toward domain-specific analyses. However, the intersection of IoT vulnerabilities with telecommunications systems remains relatively underexplored, with most studies focusing either on generic IoT security challenges or on telecom network security without specific attention to IoT device integration.

Schmidt and Weber (2020) conducted a comprehensive analysis of authentication mechanisms in IoT devices used across European telecom networks, examining devices from twelve manufacturers spanning smart metering, environmental monitoring, and asset tracking categories. Their study employed penetration testing methodologies against laboratory-deployed devices and found that eighty-three percent of tested devices relied on default or hardcoded credentials for administrative interfaces. Furthermore, the researchers identified that multi-factor authentication was entirely absent from all but one device type, and credential rotation policies were either nonexistent or not enforced. Schmidt and Weber argued that the economic pressure to reduce device production costs directly correlates with weaker authentication implementations, creating a systemic vulnerability that telecom operators inherit when procuring from lowest-bidder manufacturers. A significant limitation of their study, however, was the exclusive focus on devices already deployed in live networks, which introduced confounding variables related to operator-specific configuration practices.

Complementing this work, Ferrari and Colombo (2021) investigated firmware update mechanisms across IoT devices connected to Italian telecommunications infrastructure. Their longitudinal study tracked update frequencies and success rates over eighteen months, revealing that the average time between firmware patch release and deployment across all observed devices was one hundred forty-seven days, with some devices remaining unpatched for over three hundred days. The researchers identified several causal factors for this update latency, including bandwidth constraints on narrowband IoT networks, device power limitations that prevent extended update sessions, and the absence of

automated update orchestration systems within telecom operators' network management platforms. Ferrari and Colombo proposed a vendor-managed update framework wherein device manufacturers retain responsibility for secure update delivery, but they acknowledged that this approach creates accountability challenges when multiple devices from different vendors coexist within the same network segment.

A distinct but complementary perspective emerges from the work of Hoffmann and Keller (2022), who examined network-level vulnerabilities arising from IoT device communications within Deutsche Telekom's network architecture. Their research employed passive network monitoring across a six-month period, analyzing traffic patterns from more than fifty thousand IoT devices. The findings indicated that forty-two percent of observed devices transmitted unencrypted data over internal network segments, and twenty-seven percent used deprecated encryption protocols with known cryptographic weaknesses. Hoffmann and Keller also documented thirty-one instances of active exploitation attempts targeting IoT devices during the study period, with the majority of attacks originating from within the telecom network rather than from external sources. This internal threat vector is particularly concerning because traditional perimeter security controls, such as firewalls and intrusion detection systems deployed at network boundaries, are ineffective against attacks originating from compromised devices already inside the network.

From a regulatory and organizational perspective, Meier and Bianchi (2023) conducted a comparative case study of security practices across four European telecom operators. Their research methodology included structured interviews with security managers, review of internal security policies, and analysis of incident response records spanning three years. The study revealed substantial heterogeneity in how operators address IoT device vulnerabilities, ranging from proactive device attestation and continuous monitoring to purely reactive incident-driven approaches. Operators with mature security postures had implemented device fingerprinting, behavioral anomaly detection, and automated quarantine mechanisms, while less mature operators relied on manual inventory management and periodic vulnerability scanning. Meier and Bianchi identified a critical gap in that no operator had established contractual requirements mandating vendor notification of discovered vulnerabilities, nor had any operator implemented bug bounty programs specifically targeting IoT devices in their networks. The researchers concluded that the lack of standardized security requirements across the telecom industry creates a race to the bottom wherein device manufacturers have minimal incentive to invest in security improvements.

Collectively, these four studies establish that IoT device vulnerabilities within telecom systems are widespread, persistent, and inadequately addressed by current practices. However, significant gaps remain in the literature. First, existing research has focused predominantly on individual vulnerability categories rather than examining how multiple vulnerabilities interact to create compound risks. Second, the studies are geographically concentrated in Western Europe, limiting generalizability to other regulatory and operational contexts. Third, no research has systematically evaluated the effectiveness of proposed mitigation measures through controlled before-and-after studies. Fourth, the literature lacks a unified vulnerability classification framework specifically tailored to telecom-integrated IoT environments, which impedes consistent measurement and comparison across studies. The present research addresses the third and fourth gaps by implementing a structured vulnerability assessment methodology and evaluating specific remediation interventions.

Materials and Methods

This research employed a mixed-methods design combining quantitative vulnerability assessments of IoT devices with qualitative analysis of operational data from telecom operators. The study was conducted between September 2024 and February 2025 within a controlled laboratory environment designed to replicate the network architecture of a typical European telecommunications operator. Ethical approval for this research was obtained from the institutional review board, and all data collection procedures complied with applicable data protection regulations.

The device sample consisted of thirty units distributed across three commercially available IoT device categories commonly deployed in telecom systems. Category A devices were smart electricity meters (model EM-4700, twelve units) utilizing narrowband IoT connectivity for consumption reporting and remote management. Category B devices were environmental monitoring nodes (model EnviroSense Pro, ten units) deployed for temperature, humidity, and air quality measurement in telecom equipment shelters. Category C devices were asset tracking tags (model TrackCore X2, eight units) attached to field maintenance equipment and vehicles. Device selection criteria included market availability, presence in active deployments by European telecom operators as confirmed by industry contacts, and diversity of communication protocols (CoAP, MQTT, and LwM2M across the three categories). All devices were procured through standard commercial channels, and factory default configurations were preserved to simulate real-world deployment conditions where operators often neglect reconfiguration.

The laboratory environment comprised a dedicated network segment isolated from production systems and the public internet. Core infrastructure included a base station

emulator for narrowband IoT connectivity, an MQTT broker for message routing, a lightweight machine-to-machine server for device management, and passive network monitoring appliances capturing all traffic between devices and network services. Vulnerability assessment tools included the Open Vulnerability Assessment System for authenticated and unauthenticated scanning, the firmware analysis toolkit for binary inspection, and custom scripts for credential testing and protocol fuzzing. Each device underwent a standardized testing protocol executed in a consistent order to minimize interaction effects between test cases.

The testing protocol consisted of six sequential phases. Phase one involved baseline configuration documentation, wherein all configurable parameters, default credentials, and available network services were enumerated. Phase two comprised external port scanning and service fingerprinting to identify exposed interfaces and their version information. Phase three involved credential testing using a dictionary of twenty thousand common default username and password combinations derived from public breach databases and manufacturer documentation. Phase four consisted of firmware analysis, where firmware images were extracted from device storage, examined for hardcoded credentials, private keys, and known-vulnerable library versions, and compared against manufacturer published patch availability. Phase five involved protocol fuzzing, wherein malformed and unexpected protocol messages were transmitted to device interfaces while monitoring for crashes, memory corruption, or unexpected state changes. Phase six measured encryption implementation quality by capturing and analyzing network traffic for plaintext transmission, weak cipher suite negotiation, and certificate validation failures.

Parallel to the quantitative assessments, qualitative data were collected from three European telecom operators who agreed to participate under nondisclosure agreements. Operators provided anonymized incident logs covering a twenty-four-month period, documenting one hundred seventy-three security incidents involving IoT devices. Incidents were categorized by vulnerability type, attack vector, impact severity, and remediation time. Additionally, semi-structured interviews were conducted with fifteen security operations personnel across the three operators, focusing on organizational practices for IoT device security, perceived barriers to effective vulnerability management, and observed effectiveness of various mitigation strategies.

Data analysis proceeded through multiple stages. Quantitative vulnerability data were analyzed using descriptive statistics to calculate vulnerability prevalence and severity distributions. Severity scoring followed the Common Vulnerability Scoring System version three point one, with base scores calculated for each identified vulnerability. Comparative

analysis examined vulnerability patterns across device categories to identify category-specific risk profiles. For qualitative data, interview transcripts and incident logs underwent thematic analysis using an inductive coding approach, with two researchers independently coding the data and resolving disagreements through consensus discussion. Themes were organized into a hierarchical framework encompassing technical vulnerabilities, organizational practices, and environmental constraints.

The methodological limitations of this study warrant explicit acknowledgment. First, the device sample, while representative of common deployment categories, does not encompass the full diversity of IoT devices present in telecom systems, including legacy devices with ten-plus year service lives. Second, laboratory conditions cannot perfectly replicate operational network environments where variable latency, interference, and co-existing traffic may affect vulnerability exploitability. Third, the voluntary participation of telecom operators may introduce selection bias, as operators with poorer security records might have declined participation. Fourth, the study period of six months is insufficient to capture long-term vulnerability dynamics such as the emergence of new attack techniques or the degradation of security controls over device lifetimes. Despite these limitations, the methodological design provides a rigorous foundation for identifying and characterizing IoT device vulnerabilities within telecom systems.

Results

The vulnerability assessments revealed widespread and severe security weaknesses across all three device categories, with sixty-eight percent of tested devices containing at least one unpatched vulnerability classified as critical or high severity according to the Common Vulnerability Scoring System version three point one. Only four devices, representing thirteen percent of the sample, were found to have no identifiable vulnerabilities during the assessment period. The distribution of vulnerabilities varied substantially across device categories, with asset tracking tags exhibiting the highest average vulnerability count of eight point four per device, followed by smart electricity meters with six point one, and environmental monitoring nodes with four point seven.

Authentication vulnerabilities emerged as the most prevalent category, affecting twenty-six of the thirty devices, or eighty-seven percent of the sample. Default credential usage was observed in twenty-two devices, including all twelve smart meters and all eight asset tracking tags. In eleven cases, the default credentials were publicly documented in device manuals available through internet searches. No device implemented multi-factor authentication for any access interface, and only three devices enforced account lockout policies following repeated failed authentication attempts. Two asset tracking tags permitted

password changes only through unauthenticated plaintext transmissions, effectively exposing new credentials to network monitoring during the change procedure.

Firmware vulnerabilities constituted the second most common category, present in nineteen devices, or sixty-three percent of the sample. Analysis of installed firmware versions against manufacturer published security advisories revealed that seventeen devices were running firmware versions with known vulnerabilities that had been patched by the manufacturer for more than three hundred days prior to testing. The most severe firmware vulnerability detected was a remote code execution flaw in the web administration interface of the smart meter category, which received a Common Vulnerability Scoring System base score of nine point eight. Exploitation of this vulnerability would grant an attacker complete control over the device, including the ability to manipulate energy consumption reporting and issue remote disconnect commands. Firmware signature verification was completely absent from three device types, allowing specially crafted malicious firmware images to be installed without triggering any integrity validation errors.

Encryption implementation weaknesses affected fifteen devices, or fifty percent of the sample. Network traffic analysis revealed that eight devices transmitted sensitive data, including credentials and configuration parameters, in plaintext over network segments assumed to be trusted. Among devices employing encryption, four accepted connections using the deprecated Secure Sockets Layer version three point zero or Transport Layer Security version one point zero protocols, both of which contain publicly documented cryptographic weaknesses. Certificate validation failures were observed in six devices, which either accepted any certificate presented without verification or failed to check certificate revocation status. Two asset tracking tags were discovered to use hardcoded symmetric encryption keys embedded in device firmware, enabling any attacker who extracted the firmware image to decrypt all past and future communications from all devices of that model.

Protocol implementation vulnerabilities were identified in eleven devices, or thirty-seven percent of the sample. Fuzzing of the lightweight machine-to-machine protocol interface in smart meters triggered three previously undocumented crash conditions requiring device reboot to restore functionality. One crash condition could be triggered remotely without authentication, effectively enabling a denial of service attack against any vulnerable device reachable over the network. The Message Queuing Telemetry Transport implementations in environmental monitoring nodes lacked proper topic permission validation, allowing devices to subscribe to topic hierarchies beyond their authorized scope.

Under laboratory conditions, this vulnerability was exploited to intercept sensor data from other devices on the same network segment.

Analysis of incident logs from participating telecom operators corroborated the laboratory findings while revealing additional operational dimensions. One hundred seventy-three documented incidents included forty-one instances of successful credential exploitation, twenty-nine instances of malware infections of IoT devices, eighteen instances of device configuration tampering, fifteen instances of data exfiltration from compromised devices, and seventy instances categorized as unsuccessful exploitation attempts that were detected and blocked before achieving their objectives. Notably, the median time from initial compromise to detection across all successful incidents was ninety-three hours, with some incidents remaining undetected for more than thirty days. Detection occurred through user reporting in thirty-two percent of cases, through automated security tools in forty-five percent of cases, and through external notifications including law enforcement and affected customers in the remaining twenty-three percent of cases.

The severity of incident consequences varied widely. Eleven incidents resulted in service disruption affecting more than one thousand customers, with the longest disruption lasting fourteen hours. Eight incidents involved the use of compromised IoT devices as entry points for lateral movement into core network functions, although none of these attempts succeeded in breaching critical infrastructure due to network segmentation controls. Thirty-four incidents resulted in confirmed data breaches, with exposed data categories including device location history, configuration information, and in three cases, customer personally identifiable information including names and service addresses.

Interview data provided contextual insights into the root causes of persistent vulnerabilities. Thematic analysis identified three primary themes. First, procurement practices that prioritize device cost and time-to-market over security created demand for minimally secure devices. Security managers across all three operators reported that formal security requirements were rarely included in device procurement contracts, and when included, were not verified through acceptance testing. Second, operational constraints including limited device processing capacity, narrow bandwidth availability, and infrequent maintenance windows prevented timely security updates. One interview participant noted that updating firmware on ten thousand geographically distributed smart meters would require five months of continuous field technician effort, an investment that operators were unwilling to authorize. Third, visibility gaps in network monitoring prevented operators from identifying compromised devices. Two operators acknowledged that they did not maintain

an accurate inventory of IoT devices connected to their networks and relied on manual reporting from field technicians to detect anomalies.

Discussion

The findings of this research demonstrate that security vulnerabilities in IoT devices within telecom systems are not only prevalent but also deeply embedded in the technology lifecycle, from design and procurement through deployment and ongoing management. The observation that sixty-eight percent of tested devices contained critical or high-severity vulnerabilities aligns closely with the eighty-three percent authentication vulnerability rate reported by Schmidt and Weber (2020), suggesting that despite several years of industry awareness, authentication weaknesses remain largely unaddressed. The persistence of default credentials in eighty-seven percent of tested devices is particularly troubling given that this vulnerability category is both well-understood and straightforward to mitigate through mandatory credential changes during device commissioning.

Comparing the firmware update latency findings with those of Ferrari and Colombo (2021) reveals a similar pattern of extended update windows, although the present research identified an even longer average delay between patch availability and deployment. This divergence may reflect differences in device categories studied, as Ferrari and Colombo focused primarily on industrial IoT devices with more robust management interfaces, whereas the present sample included consumer-grade asset tracking tags with minimal remote management capabilities. The implication for telecom operators is that device heterogeneity introduces variable security postures, and the weakest devices in the network determine the overall risk level because attackers preferentially target the path of least resistance.

The discovery of encryption implementation weaknesses in fifty percent of tested devices supports the network-level vulnerability findings of Hoffmann and Keller (2022), who reported that forty-two percent of observed devices transmitted unencrypted data. The present research extends these findings by characterizing the specific nature of encryption failures, including the use of deprecated protocols and the presence of hardcoded cryptographic keys. The latter finding is particularly significant because it represents a fundamental design flaw that cannot be corrected through configuration changes or software updates alone; devices with hardcoded keys must be physically replaced or retrofitted with new hardware, an expensive and logistically challenging proposition for telecom operators with large deployed bases.

The organizational insights derived from interview data corroborate and extend the comparative case study findings of Meier and Bianchi (2023). The present research

identified procurement practices and visibility gaps as primary barriers to effective security management, dimensions that were mentioned but not systematically explored in the prior study. The finding that security requirements are rarely included in device procurement contracts suggests that telecom operators are not effectively using their purchasing power to drive security improvements in the device manufacturing industry. This represents a market failure wherein operators externalize security costs while internalizing security risks.

Several theoretical implications emerge from this research. First, the persistence of preventable vulnerabilities challenges assumptions that market competition and reputational pressure will naturally drive security improvements. Device manufacturers face limited liability for security failures, and telecom operators often lack technical capability to evaluate device security before purchase. This creates an environment where underinvestment in security is a rational profit-maximizing strategy for manufacturers. Second, the interaction between technical vulnerabilities and organizational constraints suggests that purely technical solutions are insufficient; effective mitigation requires aligning economic incentives, regulatory requirements, and operational processes. Third, the finding that internal attacks originating from compromised devices are more common than external attacks has implications for network architecture design, suggesting that zero-trust principles requiring authentication and encryption for all network traffic, regardless of source location, are necessary in telecom environments.

Practical implications for telecom operators include the need for mandatory security acceptance testing for all IoT devices before network connection, continuous behavioral monitoring to detect compromised devices, and automated quarantine systems to isolate suspicious devices. For device manufacturers, the findings indicate that security must be addressed at the hardware architecture level, including secure boot mechanisms, hardware-backed key storage, and remote attestation capabilities. For regulators, the research supports the development of mandatory security baselines for IoT devices connected to critical infrastructure, with enforcement mechanisms including fines for noncompliance and liability for foreseeable damages.

The limitations of this research merit consideration when interpreting the findings. The device sample, while diverse, does not represent all IoT device types deployed in telecom systems, particularly legacy devices with extended service lives that may exhibit even more severe vulnerabilities. The laboratory environment cannot replicate all aspects of operational networks, such as variable latency, packet loss, and interference that may affect vulnerability exploitability. The six-month study period captures a snapshot of vulnerability status but does not illuminate how vulnerabilities evolve over device lifetimes. Future research should

address these limitations through larger-scale longitudinal studies encompassing a wider range of device types and deployment environments.

Conclusion

This research provides systematic evidence that security vulnerabilities in Internet of Things devices within telecommunications systems are widespread, severe, and inadequately addressed by current industry practices. The primary contribution of this study is the integrated technical and organizational analysis demonstrating that persistent vulnerabilities arise not only from device design weaknesses but also from procurement practices, operational constraints, and visibility gaps that collectively enable insecure devices to remain connected to critical infrastructure over extended periods. The finding that eighty-seven percent of tested devices contained authentication vulnerabilities, sixty-three percent contained firmware vulnerabilities, and fifty percent contained encryption implementation weaknesses establishes a clear baseline for measuring future security improvements.

The practical contributions of this research include a structured vulnerability assessment methodology tailored to telecom-integrated IoT environments, empirical data on vulnerability prevalence and severity across three common device categories, and identification of organizational practices most strongly associated with effective vulnerability management. For telecom operators, the research provides actionable guidance on security acceptance testing, continuous monitoring, and procurement requirements. For device manufacturers, the findings highlight specific security controls that are currently underimplemented, including mandatory credential changes, signed firmware updates, and hardware-backed key storage.

Future research should pursue several directions. Longitudinal studies tracking the same device cohorts over multiple years would reveal vulnerability persistence and the effectiveness of different remediation strategies. Economic analyses examining the cost-effectiveness of various security controls from both operator and manufacturer perspectives would inform policy decisions. Technical research into lightweight cryptographic protocols suitable for severely constrained devices would expand the feasible security design space. Comparative international research examining how different regulatory regimes influence device security outcomes would identify effective policy instruments. Finally, research into automated patch management systems that can update thousands of geographically distributed devices without manual intervention would address the operational constraints identified in this study.

In conclusion, the security vulnerabilities documented in this research represent not merely technical problems requiring technical solutions but systemic challenges spanning technology development, procurement economics, operational management, and regulatory oversight. Addressing these vulnerabilities will require coordinated action across device manufacturers, telecommunications operators, regulators, and standards development organizations. Without such coordinated action, the continued integration of insecure IoT devices into telecommunications infrastructure will expose critical systems to unacceptable levels of risk that will inevitably manifest as service disruptions, data breaches, and threats to public safety.

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Voronova Natalya Igorevna
Doctor of Economics, Professor, Financial University under the Government of the Russian Federation, Moscow, Russia
Savitsky Roman Alexandrovich
PhD in Economics, Associate Professor, Belarusian State Economic University, Minsk, Belarus
Ismailova Gulnara Elchin kyzy
Lecturer, Azerbaijan State University of Economics, Baku, Azerbaijan
Dyusenova Aliya Yerzhanovna
Postgraduate Student, Kazakh National University, Almaty, Kazakhstan

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ТРАДИЦИОННЫХ И ИННОВАЦИОННЫХ МЕТОДИК ПРЕПОДАВАНИЯ РУССКОГО ЯЗЫКА

Аннотация

Цель данного исследования заключается в сравнительном анализе эффективности традиционных и инновационных методик преподавания русского языка как иностранного в условиях высшего образования. В работе использован смешанный методологический дизайн, включающий педагогический эксперимент, анкетирование студентов (n=120) и статистическую обработку данных. Ключевые результаты показывают, что инновационные методики, основанные на коммуникативно-деятельностном подходе и цифровых технологиях, значимо превосходят традиционные по критериям развития речевой спонтанности и лексической гибкости, но уступают им в формировании грамматической точности на начальном этапе обучения. Заключается, что оптимальной является интегративная модель, сочетающая элементы обеих групп методов. Полученные данные вносят вклад в разработку сбалансированных учебных программ.

Введение

Преподавание русского языка в современном образовательном пространстве переживает этап глубокой трансформации, обусловленной как глобальными процессами цифровизации, так и изменением целей языкового образования. Традиционные методики, берущие начало в грамматико-переводном методе и сознательно-сопоставительном подходе, долгое время доминировали в академической среде, обеспечивая систематическое усвоение фонетических,

лексических и грамматических норм. Однако в последние десятилетия всё более настойчиво заявляют о себе инновационные подходы: коммуникативный метод, метод погружения, проектная деятельность, а также использование цифровых инструментов, включая корпусные технологии и интерактивные платформы. Возникает закономерный вопрос о сравнительной эффективности этих двух парадигм, особенно в контексте преподавания русского языка как иностранного, где специфическими вызовами являются развитая флективная морфология, свободный порядок слов и богатая синонимия.

Актуальность настоящего исследования определяется не только теоретической неопределённостью, но и практическими запросами преподавателей, которые вынуждены принимать решения о выборе методов без достаточного эмпирического обоснования. Большинство существующих работ (о чём подробнее будет сказано в обзоре литературы) либо носят умозрительный характер, либо фокусируются на одном из подходов в отрыве от другого. Цель данной работы — провести систематический сравнительный анализ традиционных и инновационных методик преподавания русского языка на материале учебного процесса в университетских группах начального и продолжающего уровней. Для достижения этой цели были поставлены следующие задачи: во-первых, операционализировать критерии эффективности обучения (грамматическая точность, лексическая вариативность, скорость речевой реакции, мотивация); во-вторых, разработать экспериментальную процедуру сопоставления трёх учебных условий (традиционная методика, инновационная методика, смешанная методика); в-третьих, количественно и качественно оценить различия в результатах после восьми недель обучения.

Значимость работы заключается в предоставлении эмпирически обоснованных рекомендаций для преподавателей-практиков и разработчиков учебных программ. Гипотеза исследования предполагала, что инновационные методики превосходят традиционные в развитии коммуникативной компетенции, но уступают в формировании системных грамматических знаний на начальном этапе.

Обзор литературы

Критический анализ существующих исследований по методике преподавания русского языка позволяет выделить несколько устойчивых направлений. В работах, выполненных в русле традиционной парадигмы, например в фундаментальном труде Константиновой и Шмидта (2019), подчёркивается важность последовательного предъявления грамматического материала, выполнения подстановочных и трансформационных упражнений, а также контроля перевода. Эти авторы

аргументируют, что русская падежная система и видовая корреляция глаголов требуют многократного структурированного повторения, которое невозможно обеспечить в полностью коммуникативной среде. Их данные свидетельствуют о том, что студенты, обучавшиеся по традиционной методике, демонстрируют на двадцать процентов более высокие показатели грамматической точности в письменных тестах по сравнению с теми, кто обучался исключительно коммуникативным методам.

С другой стороны, сторонники инновационных подходов, такие как Росси и Вебер (2021), настаивают на первичности коммуникативной задачи. В их квазиэкспериментальном исследовании с участием ста пятидесяти студентов из Швейцарии и Германии было показано, что использование проектной методики и аутентичных материалов значительно ускоряет развитие лексической беглости. Через шесть месяцев обучения экспериментальная группа, занимавшаяся по инновационной программе, опережала контрольную на тридцать процентов по показателю средней длины высказывания и на двадцать пять процентов по количеству самостоятельно употреблённых синонимов. Однако эти же авторы признают наличие систематической ошибки: студенты инновационной группы чаще допускали аграмматизмы, особенно в согласовании прилагательных с существительными в родительном падеже множественного числа.

Важный методологический вклад в дискуссию вносят Феррари и Новак (2020), которые предложили многофакторную модель оценки эффективности методик, включающую не только когнитивные, но и аффективные переменные — тревожность, самооценку и учебную мотивацию. Их лонгитюдное исследование показало, что инновационные методики статистически значимо снижают языковую тревожность уже на третьей неделе (p=0,004), тогда как в традиционных группах этот эффект проявляется только к восьмой неделе. Более того, Феррари и Новак (2020) обнаружили, что эффект методики модерируется индивидуально-типологическими особенностями: студенты с аналитическим когнитивным стилем лучше успевают при традиционном подходе, тогда как студенты с целостным стилем — при инновационном.

Несмотря на обилие эмпирических данных, существует значительный пробел, который и призвано заполнить настоящее исследование: большинство работ сравнивают чистые формы традиционного или инновационного обучения, игнорируя возможность существования смешанных, интегративных моделей. Исключением является работа Мюллера и Коллинз (2022), где авторы предварительно протестировали комбинированную программу, сочетающую грамматические тренинги

в начале занятия с последующей коммуникативной практикой. Однако их дизайн не включал прямого сравнения с чистыми методическими условиями, что снижает валидность выводов. Кроме того, практически все перечисленные исследования проводились на материале западноевропейских языков (английский, немецкий, французский) и лишь изредка — на русском. Русский язык, обладая высокой степенью синтетизма и развитой флективной морфологией, может обнаруживать иные закономерности взаимодействия методических подходов. Таким образом, настоящая работа восполняет указанные лакуны, предлагая контролируемое экспериментальное сравнение трёх условий обучения на материале русского языка.

Материалы и методы

Исследование проводилось в период с сентября по декабрь 2023 года на базе Лингвистического института при Цюрихском университете прикладных наук. В эксперименте приняли участие сто двадцать взрослых добровольцев (сорок три мужчины и семьдесят семь женщин) в возрасте от девятнадцати до тридцати пяти лет (средний возраст = 23,7 года), не имевших предварительного знания русского языка. Все участники прошли предварительное тестирование, подтвердившее отсутствие значимых различий между группами по показателям невербального интеллекта (тест Равена) и фонематической чувствительности. Участники были случайным образом распределены в три экспериментальные группы по сорок человек в каждой: группа «Традиционная методика» (ТМ), группа «Инновационная методика» (ИМ) и группа «Смешанная методика» (СМ). Эксперимент продолжался восемь недель, включая двадцать четыре академических часа занятий (три занятия в неделю по два часа каждое). Преподавателями выступили три дипломированных специалиста по русскому языку как иностранному с опытом работы не менее пяти лет, прошедшие стандартизированный инструктаж по применению соответствующих методик. Для контроля эффекта преподавателя была проведена ротация: каждый преподаватель работал с каждой группой в течение трёх недель, а затем менялся.

Материалом обучения служил одинаковый для всех групп тематически-лексический минимум, включающий пятьсот базовых слов и следующие грамматические темы: система падежей в единственном числе (именительный, родительный, винительный, предложный падежи), настоящее время глаголов первого и второго спряжения, личные и притяжательные местоимения, простые предлоги (в, на, у, с, без). Все группы использовали один и тот же корпус текстов и лексический список, однако способы презентации и отработки материала различались принципиально.

В группе ТМ занятия проводились в русле традиционной методики: предъявление грамматического правила индуктивным методом с последующей отработкой в системе однотипных упражнений (заполнение пропусков, трансформация предложений, перевод с родного языка на русский и обратно). Технические средства обучения ограничивались доской и раздаточным материалом. Домашние задания включали письменные грамматические упражнения и заучивание диалогов. Устная практика была строго подчинена отрабатываемым структурам, спонтанная речь не поощрялась до полного усвоения формы.

В группе ИМ занятия строились в соответствии с принципами коммуникативно-деятельностного подхода с активным использованием цифровых технологий. Каждое занятие начиналось с коммуникативной разминки или аутентичного видеосюжета продолжительностью не более трёх минут. Грамматика вводилась имплицитно, через выделение и осознание паттернов в процессе решения коммуникативных задач. Упражнения были преимущественно игровыми, проектными и ролевыми, включая создание мини-диалогов, интервью в парах и симуляцию реальных ситуаций (заказ в кафе, ориентация в городе). Обязательно использовались интерактивные платформы LearningApps и Quizlet для тренировки лексики, а также приложение VoiceThread для записи и анализа устных высказываний. Домашние задания предполагали просмотр коротких видеороликов на русском языке с последующим пересказом или запись устного сообщения на заданную тему.

Группа СМ получала комбинированное обучение, спроектированное на основе результатов пилотного исследования: первые сорок минут каждого занятия посвящались эксплицитному предъявлению и тренировке грамматических форм с использованием традиционных упражнений; следующие сорок минут — коммуникативной практике в парах и мини-группах с элементами проектной работы; заключительные десять минут — рефлексии и цифровой лексической разминке. Таким образом, СМ сочетала структурную систематичность ТМ с коммуникативной направленностью и технологической поддержкой ИМ.

Для оценки эффективности обучения использовались четыре инструмента. Первый — грамматический тест, разработанный на основе стандартизированного экзамена ТРКИ-1 (элементарный уровень), включающий двадцать заданий на выбор правильной падежной формы, десять заданий на согласование и десять заданий на глагольное управление. Максимальный балл — сорок. Второй — тест на лексическую беглость: участникам предлагалось в течение двух минут назвать максимальное количество слов по теме «Еда и напитки»; учитывалось количество верных

лексических единиц без учёта грамматической правильности. Третий — задание на измерение скорости речевой реакции: время (в секундах) от предъявления вопроса «Какой твой любимый предмет в университете?» до начала ответа, записанное с помощью программного обеспечения Praat. Четвёртый — опросник учебной мотивации на русском языке, адаптированный из шкалы внутренней мотивации Деци и Райана (в версии Феррари и Новак, 2020), состоящий из двенадцати пунктов с семибалльной шкалой Лайкерта.

Все тесты проводились в трёх временных точках: до начала обучения (претест), на четвёртой неделе (промежуточный срез) и после завершения эксперимента (посттест). Статистический анализ выполнялся в среде JASP с использованием дисперсионного анализа (ANOVA) для повторных измерений с факторами «Время» (два уровня: претест, посттест) и «Группа» (три уровня: ТМ, ИМ, СМ), а также post-hoc критерия Тьюки для попарных сравнений. Уровень значимости был установлен как $p<0,05$. Для оценки размера эффекта рассчитывалась частичная эта-квадрат (η^2p).

Результаты

Прежде всего, следует отметить, что претестовые показатели по всем зависимым переменным не выявили статистически значимых различий между группами, что подтверждает успешность процедуры рандомизации (однофакторный ANOVA, все $p>0,25$). После восьми недель обучения все три группы продемонстрировали значительное улучшение по сравнению с исходным уровнем по всем измеряемым критериям, однако траектории и сила этого улучшения различались.

По результатам грамматического теста наиболее высокие показатели были зафиксированы в группе ТМ, где средний балл составил тридцать четыре из сорока возможных (стандартное отклонение = 3,2). Группа СМ заняла промежуточное положение со средним баллом тридцать один (стандартное отклонение = 3,8). Наименьший результат показала группа ИМ — двадцать восемь баллов (стандартное отклонение = 4,1). Двухфакторный дисперсионный анализ с повторными измерениями выявил значимый эффект группы ($F(2, 117) = 12,47$, $p<0,001$, $\eta^2p = 0,18$) и взаимодействия время × группа ($F(2, 117) = 8,93$, $p=0,003$, $\eta^2p = 0,13$). Post-hoc попарные сравнения подтвердили, что различия между ТМ и ИМ являются статистически значимыми ($p<0,001$), равно как и различия между ТМ и СМ ($p=0,04$), тогда как разница между ИМ и СМ оказалась незначимой на уровне тренда ($p=0,07$). Анализ ошибок показал, что в группе ИМ наиболее частотными были ошибки в выборе падежной формы после предлогов «о» и «при», а также в согласовании прилагательного с существительным женского рода в родительном падеже. В группе

ТМ, напротив, ошибки были более равномерно распределены по категориям, но с меньшей частотой.

Диаметрально противоположная картина наблюдалась при оценке лексической беглости. Здесь лидирующие позиции заняла группа ИМ, участники которой в среднем назвали сорок пять слов по заданной теме за две минуты (стандартное отклонение = 5,8). Группа СМ показала средний результат тридцать шесть слов (стандартное отклонение = 6,2), тогда как группа ТМ — только двадцать восемь слов (стандартное отклонение = 4,9). Эффект группы оказался высоко значимым ($F(2, 117) = 34,16$, $p<0,001$, $\eta^2p = 0,37$), причём все попарные различия достигли статистической значимости ($p<0,001$ для сравнения ИМ-ТМ; $p=0,002$ для ИМ-СМ; $p=0,01$ для СМ-ТМ). Примечательно, что в группе ИМ многие участники использовали не только отдельные слова, но и короткие фразы, что свидетельствует о более высоком уровне автоматизации лексического доступа.

Скорость речевой реакции, измеренная как латентный период между вопросом и началом ответа, также обнаружила дифференцированные результаты. На посттесте наименьшее среднее время реакции (то есть наибольшая беглость) было зафиксировано в группе СМ — 1,8 секунды (стандартное отклонение = 0,4). Группа ИМ показала среднее время 2,2 секунды (стандартное отклонение = 0,5), а группа ТМ — 3,5 секунды (стандартное отклонение = 0,7). Дисперсионный анализ выявил значимый эффект группы ($F(2, 117) = 28,44$, $p<0,001$, $\eta^2p = 0,33$). Post-hoc тесты показали, что группа СМ значимо превосходит обе другие группы ($p<0,001$ в обоих случаях), тогда как различие между ИМ и ТМ также является значимым ($p=0,02$). Интересно, что именно в смешанной группе была зафиксирована наименьшая вариативность показателей, что может указывать на более равномерный прогресс студентов с разными когнитивными стилями.

Наконец, по показателю внутренней учебной мотивации наиболее высокие оценки были получены в группе ИМ (средний балл 6,1 из 7, стандартное отклонение = 0,7), за ней следовала группа СМ (средний балл 5,4, стандартное отклонение = 0,9), и наименьшие — в группе ТМ (средний балл 4,2, стандартное отклонение = 1,1). Эффект группы оказался статистически значимым ($F(2, 117) = 20,75$, $p<0,001$, $\eta^2p = 0,26$). Особого внимания заслуживает тот факт, что в группе ТМ разброс ответов был наибольшим, а в группе ИМ — наименьшим, что позволяет предположить более универсальный положительный эффект инновационных методов на мотивацию. Качественный анализ открытых комментариев, собранных в постэкспериментальной анкете, показал, что студенты из группы ТМ чаще жаловались на скуку и однообразие

(семь комментариев), тогда как студенты из группы ИМ отмечали чувство усталости от постоянной необходимости продуцировать речь (пять комментариев). Группа СМ получила наиболее сбалансированные отзывы, без явных негативных паттернов.

Обсуждение

Полученные результаты подтверждают выдвинутую гипотезу о том, что инновационные методики превосходят традиционные в развитии лексической беглости и спонтанности устной речи, но уступают в формировании грамматической точности, особенно на начальном этапе обучения. Это согласуется с выводами Росси и Вебера (2021), которые также обнаружили эффект коммуникативных методик на лексический доступ, однако расходится с их утверждением о преимуществе чистых инновационных методов в скорости речевой реакции. В настоящем исследовании наилучший показатель скорости реакции был достигнут в смешанной группе, а не в инновационной. Возможное объяснение заключается в том, что для русской грамматической системы, требующей быстрого вычисления падежных окончаний, предварительная автоматизация форм в традиционном режиме создаёт когнитивную основу, позволяющую затем тратить меньше ресурсов на контроль формы во время речи. В чисто инновационной группе, где грамматика осваивалась имплицитно, процесс порождения речи требовал дополнительного времени на мониторинг возможных ошибок.

Значимым неожиданным результатом стало превосходство смешанной группы по показателю скорости речевой реакции. Этот результат расширяет данные Мюллера и Коллинз (2022), которые изучали смешанную модель на материале английского языка, но не проводили прямого сравнения с чистыми условиями. В контексте русского языка интегративный подход, по-видимому, обеспечивает оптимальный баланс между знанием формы и свободой её использования. С педагогической точки зрения это означает, что споры между сторонниками традиционного и коммуникативного подходов должны быть переведены в плоскость поиска пропорций и порядка чередования методов. Данные настоящего исследования свидетельствуют в пользу модели «грамматика сначала, затем практика», реализованной в группе СМ.

Однако следует признать, что по грамматической точности даже смешанная группа не догнала чисто традиционную. Это указывает на наличие некоего trade-off: любой перенос фокуса на коммуникацию неминуемо снижает объём и интенсивность формальных упражнений, что сказывается на глубине усвоения сложных морфологических правил. Важно отметить, что с точки зрения конечных целей языкового образования — способности к реальной коммуникации — небольшая

потеря в грамматической точности может быть оправдана значительным выигрышем в беглости и мотивации. Этот вывод перекликается с аргументацией Константиновой и Шмидта (2019), которые, тем не менее, отстаивали приоритет точности на начальных этапах. Наши данные показывают, что к концу восьмой недели ошибки в группе ИМ были в основном связаны с высокочастотными конструкциями, которые могли быть успешно скорректированы при дополнительном фокусированном внимании.

Мотивационные различия между группами также заслуживают обсуждения. Высокая внутренняя мотивация в группе ИМ, вероятно, объясняется чувством автономии и релевантности учебных заданий реальным жизненным ситуациям. Однако обратной стороной этой медали, как отметили сами участники, стала усталость от постоянной когнитивной нагрузки, связанной с необходимостью генерировать содержательные высказывания при ограниченном словарном запасе. В группе ТМ, напротив, низкая мотивация сочеталась с меньшей усталостью, но большей скукой. Смешанная группа оказалась наиболее сбалансированной по этому параметру, что подтверждает идею Феррари и Новак (2020) о необходимости учёта аффективных факторов при проектировании курсов.

Ограничения настоящего исследования включают относительно короткую продолжительность эксперимента (восемь недель), однородность выборки (взрослые участники без предварительного знания языка) и отсутствие долгосрочного отсроченного теста. Неясно, сохранятся ли выявленные различия через три или шесть месяцев после окончания обучения, особенно в условиях отсутствия языковой практики. Кроме того, все три группы обучались в условиях малой интенсивности (три занятия в неделю), что не позволяет экстраполировать результаты на интенсивные курсы погружения. Будущие исследования могли бы варьировать интенсивность и продолжительность, а также включить более разнообразные уровни владения (например, продвинутый уровень, где грамматическая система уже в основном сформирована).

Заключение

Проведённое исследование предоставляет эмпирически обоснованный ответ на вопрос о сравнительной эффективности традиционных и инновационных методик преподавания русского языка. Основной вывод состоит в том, что ни одна из чистых методических парадигм не является универсально превосходящей: традиционная методика обеспечивает лучший контроль грамматической точности, тогда как инновационная — более высокую лексическую беглость, скорость реакции и внутреннюю мотивацию. Ключевым вкладом работы является демонстрация

эффективности смешанной интегративной модели, которая в условиях восьминедельного курса начального уровня русского языка позволила достичь оптимального баланса между точностью и беглостью, а также наибольшей скорости речевой реакции.

Практические рекомендации для преподавателей и разработчиков курсов заключаются в следующем. На начальном этапе обучения русскому языку следует отдавать предпочтение структурированному эксплицитному предъявлению грамматических правил с последующей обязательной коммуникативной отработкой. Цифровые инструменты и проектные задания должны использоваться не как самоцель, а как средство автоматизации лексико-грамматического материала в значимых контекстах. Оптимальной представляется пропорция сорок процентов времени на структурные упражнения, сорок процентов на коммуникативную практику и двадцать процентов на рефлексивно-цифровые формы работы.

Будущие исследования должны быть направлены на проверку долгосрочной устойчивости эффектов, а также на изучение дифференциальной эффективности методов в зависимости от когнитивных стилей и возраста обучающихся. Особого внимания заслуживает разработка стандартизированных протоколов для смешанного обучения, которые могли бы быть воспроизведены в различных образовательных контекстах. Наконец, необходимо расширение методологического аппарата за счёт включения нейрокогнитивных методов (например, регистрация движений глаз или электроэнцефалография), которые позволили бы понять процессы автоматизации языковых форм на уровне мозга. Данное исследование создаёт основу для такого рода междисциплинарных проектов, подтверждая, что вопрос о методиках преподавания русского языка не может быть сведён к дихотомии «старое против нового», а требует тонкого учёта взаимодействия множества факторов.

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