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Digitalization of Railway Traffic Dispatching Systems: From Legacy Infrastructure to a Software-Centric Platform

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Abstract

Digitalization of railway traffic dispatching systems is a key step in the modernization of railway telecommunication infrastructure. This paper presents a case study of the migration from legacy analog technology to a software-centric dispatching platform that integrates digital signal processing, optical fiber transmission, and Internet Protocol (IP)-based network architectures, as implemented in the Serbian railway system. The modernization is performed through an iterative, incremental process: existing analog dispatcher equipment and established operating procedures are preserved, while digital dispatching centers, trackside communication nodes, and radio-dispatching services are introduced gradually. This staged evolution enables high-capacity, noise-resilient communication and seamless interconnection between the old and the new subsystems without disrupting railway operations. The adoption of software-based control and integrated digital signal processing provides modular scalability, real-time system supervision, automated diagnostics, and improved maintainability. One of critical services within the new architecture, the Centralized Call Record- and Message-Archiving System (CCRMAS), provides a centralized platform that captures, secures, and retrieves operational railway communication in real time for monitoring, post-incident analysis, and regulatory compliance. The resulting architecture, deployed within Serbian Railways, establishes a scalable and resilient foundation for future automation, interoperability, and integration within intelligent railway traffic-management environments. Thus, the paper extracts a generalizable hybrid migration architecture model and transferable design principles, supported by deployment artifacts and illustrated through migration scenarios, that can be applied to the modernization of other legacy-intensive railway networks.

Keywords: railway telecommunication; digital transformation; digital dispatching; software-centric architecture; voice recording; message recording; legacy system integration



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1. Introduction

Dispatching systems represent a vital component of modern railway communication infrastructure. As an important operational element within railway transport, they provide centralized supervision, coordination of dispatcher activities, and support for operational workflows through voice communication and structured message exchange. Dispatching systems provide the essential real-time voice and data communication channels between

dispatchers in control centers, trackside equipment, and train crews, thereby ensuring the operational integrity and safety of the entire railway network [1–4].

In recent decades, the digitalization of railway infrastructure has become a strategic priority worldwide [1,2,5–10]. Driven by advancements in signaling, telecommunications, data processing and automation, modern railways are evolving into integrated, software-defined environments that support higher traffic capacity, improved safety and interoperable operations [3]. Within this broader transformation, the modernization of dispatching systems represents a foundational component, as reliable voice and data communication is essential for train movement and operational coordination across the network.

Modern dispatching systems are no longer limited to basic voice communication and message exchange. They integrate advanced functionalities such as remote monitoring, real-time diagnostics, automated fault detection, and automatic recovery of telecommunication nodes. In the context of European railway networks, these developments align with the broader objectives of the European Rail Traffic Management System (ERTMS) and corresponding Technical Specifications for Interoperability (TSIs), which emphasize harmonized communication and safe command–control architectures [11,12]. The adoption of digital protocols such as Voice over Internet Protocol (VoIP), as well as widespread deployment of optical fiber transmission, has enabled a new generation of dispatching systems characterized by high availability, redundancy, and strong interoperability with signaling, telecom, and traction-power subsystems.

In many railway networks, however, dispatcher and field personnel communication still relies on long-lived analogue infrastructure (copper interconnections, analog radio, and tone-based signaling) that was designed for reliability and simplicity rather than interoperability, automation, and auditability. As railways modernize toward IP-based transmission, software-defined control, and integrated supervision, dispatching systems become a key migration bottleneck: they must evolve without interrupting operations and without breaking established procedures and interfaces that are tightly coupled to operational communication practices and staff training. A major challenge in this domain is that full “rip-and-replace” upgrades are often infeasible. Railway dispatching is embedded within critical workflows and geographically distributed infrastructure and is subject to strict regulatory requirements, ensuring the traceability of voice and data communication. Consequently, the central research problem is not only how to design a modern dispatching communication platform, but how to migrate legacy dispatching ecosystems in a controlled manner, preserving backward compatibility while introducing new digital capabilities such as centralized supervision, fault tolerance, and integrity-protected archiving of voice and operational command/notification messages.

Prior work on railway digitalization often emphasizes mobile communication evolution (e.g., Global System for Mobile Communications–Railway—GSM-R successors and Future Railway Mobile Communication System—FRMCS) and high-level architectures for interoperable rail systems [13]; while these developments are essential, many networks operate in a transitional reality where dispatching communication over analog fixed-lines, tone-based radio signaling, and new IP backbones must coexist for extended periods. This raises open practical-research questions about hybrid integration strategies, interface preservation, and evidence-grade recording across heterogeneous wired and radio domains—especially when modernization is driven by operational constraints rather than greenfield deployment.

This paper examines these challenges through a design-oriented case study of the Serbian railway dispatching modernization [14], where legacy analog dispatching infrastructure is progressively migrated to a software-centric platform. The analyzed integrated environment combines three functional subsystems: a fixed-line Railway Dispatching Cen-

tral System (RDCS), a Digital Radio-Dispatching System (DRDS) that preserves operational radio procedures while introducing digital transport and supervision, and a Centralized Call Record- and Message-Archiving System (CCRMAS) that provides integrity-protected capture and retrieval of dispatcher voice records and structured command/notification messages across both domains. The case study system exclusively addresses operational voice communication, operational messages exchange and supervision rather than performing centralized traffic control, route setting, or safety-critical train movement authorization. It remains human-mediated and functionally independent of interlocking, signaling, and train control systems. While the presented implementation primarily interfaces existing fixed-line trackside and radio communication points, the proposed architecture is not limited to these domains; it is designed as an extensible integration layer that can interoperate with other current and emerging railway communication architectures, thereby supporting subsequent stages of system modernization without fundamental redesign.

The design work was guided by the following objectives:

- To investigate architectural approaches that enable incremental migration from analog dispatching to an IP-based, software-centric platform while maintaining operational continuity and backward compatibility;
- To analyze mechanisms for unified and auditable recording and archiving of dispatcher voice communication and operational command/notification messages, suitable for post-incident analysis and regulatory compliance;
- To derive transferable design principles that can inform similar modernization efforts in other legacy-heavy railway networks.

Based on these objectives, the paper examines how architectural choices can be validated under real operational constraints in legacy-heavy railway dispatching environments without disrupting ongoing operations or requiring simultaneous replacement of all field equipment. Rather than focusing on component-level optimization, this work adopts a system-level, design-oriented research approach, in which architectural choices are validated through operational deployment and structured evaluation under real-world constraints.

The investigation is structured around the following research questions:

- RQ1: Which architectural mechanisms enable coexistence of analog dispatching endpoints with a software-enabled IP core without altering established operational workflows?
- RQ2: How can dispatcher voice communication and command/notification messages be captured, verified, and archived in a unified and auditable manner across heterogeneous wired and radio domains?
- RQ3: Which system-level indicators and operational metrics are sufficient to validate reliability, traceability, and communication quality in a live railway environment where controlled experiments are not feasible?
- RQ4: Which architectural and methodological principles derived from the case study are transferable to other legacy-heavy railway networks?

In addressing these questions, the paper makes three main contributions.

First, it presents a migration-oriented dispatching architecture that explicitly supports the hybrid coexistence of legacy analog endpoints with an IP-based core, enabling staged modernization without service interruption or wholesale replacement of field equipment.

Second, it introduces an integrated approach to call record and message archiving, implemented through the CCRMAS subsystem, which unifies dispatcher voice recording with command and notification message archiving, provides integrity verification and consistent time-aligned indexing, and enables event correlation across multiple subsystems for audit, compliance, and post-incident analysis.

Third, based on deployment in an operational railway environment, the paper distills a generalizable hybrid migration architecture model, a structured set of design principles, deployment-level artifacts, and implementation steps that abstract system-specific details. They are intended to be transferable to other railway networks facing similar legacy constraints and regulatory requirements.

Beyond the specific deployment context, the contributions of this work are framed as generalizable solutions to recurring structural problems in modernization of rail dispatching. Modernizing rail dispatching in legacy-heavy networks faces persistent challenges: long-lived field equipment and established procedures create barriers to digital transformation, continuous service requirements make full system replacement infeasible, and heterogeneous communication domains limit traceability and accountability. This work introduces three architectural patterns to address these challenges: interface-level adaptation, which preserves external operational behavior while modernizing internal communication; incremental migration, which enables staged coexistence of analog and digital components; and unified integrity-verified archiving, which consolidates cross-domain communications with cryptographic verification for system-level accountability. Together, these approaches provide transferable solutions for evolving dispatching systems in technologically, operationally, and regulatory diverse railway environments, extending beyond the Serbian case study.

The remainder of this paper is organized as follows. Section 2 reviews related work on the digitalization of railway dispatching and communication systems, with particular attention to hybrid analog–digital environments and incremental modernization approaches. Section 3 outlines the adopted design-oriented and system-level research methodology and the criteria used for system-level validation. Section 4 constitutes the technical core of the paper and presents the proposed software-centric dispatching architecture, detailing the design, integration, and operational realization of the RDCS, DRDS, and CCRMAS subsystems. Section 5 evaluates the proposed architecture through system-level operational analysis under live conditions, with particular focus on continuity during migration, preservation of dispatcher workflows, unified integrity-protected archiving, communication performance indicators, and system resilience, and subsequently provides a comparison with the legacy analog system. Section 6 formalizes the generalizable hybrid migration architecture model, derives transferable architectural and methodological design principles, and specifies deployment-level reproducibility artifacts, protocol constraints, and migration scenarios applicable to other legacy-heavy railway networks. Finally, Sections 7 and 8 conclude the paper by providing a structured response to the research questions formulated in Section 1, synthesizing the validated architectural contributions and outlining directions for further evolution toward interoperable, software-defined railway communication environments.

2. Related Work

Early dispatcher networks, based on analog wired and radio communication, provided the first operational framework for railway command and control and formed the backbone of conventional railway networks throughout much of the twentieth century [15]. These systems were characterized by high robustness and operational resilience, but offered limited integration with signaling subsystems, minimal real-time data exchange, and little support for decision assistance beyond basic voice coordination. Consequently, early modernization efforts focused on computer-assisted dispatching tools and optimization-based models to support conflict resolution, train path allocation, and schedule adherence [15]. The emergence of high-speed railways further reshaped dispatching requirements by promoting centralized control structures, standardized interfaces, and continuous dispatcher–train connectivity along dedicated corridors [16].

With advances in telecommunication and information technologies, dispatching systems gradually evolved toward digital and software-based platforms capable of supporting integrated monitoring, supervision, and control functions [7–10]. A key enabling factor in this transition was the replacement of copper transmission lines with optical fiber infrastructure, which facilitated the deployment of IP-based multi-service backbones carrying both legacy voice services and emerging data applications. Modern railway telecommunication architectures increasingly integrate dispatching, signaling, telecommand, and telemetry within unified digital environments, while preserving logical separation to meet safety and reliability requirements [17].

In parallel with dispatching-system evolution, significant research and standardization efforts have focused on the development of railway mobile communication technologies. Systems such as GSM-R, its proposed successor LTE-R (Long-Term Evolution for Railways), and the emerging FRMCS define how train-to-ground communication is realized at the radio and network levels, particularly for mobile units and safety-critical services [8,9,13,18–22]. These technologies primarily address bandwidth, latency, availability, and interoperability of mobile communication. Importantly, they do not prescribe the internal architecture of dispatching systems, the organization of fixed-line communication, or the mechanisms for unified recording and archiving of dispatcher communication, which remain system-level design challenges largely independent of the underlying radio technology.

As a result, many railway networks operate in hybrid operational environments, where analog fixed-line dispatching, tone-based radio signaling, GSM-R, and IP-based transmission coexist for extended periods. The deployment of ERTMS across Europe further highlights this coexistence: while ERTMS and FRMCS standardize train control and mobile communication, dispatching systems must still integrate heterogeneous communication domains and support long asset life-cycles during gradual migration phases [10,23].

Country-specific implementations illustrate the diversity of dispatching modernization paths. For example, Uzbekistan’s Digital Railway programme emphasizes automated dispatching centers and digital monitoring platforms while retaining selected legacy sub-systems [24]. The Kamchik tunnel employs a digital mobile radio system to replace obsolete analog radio, improving coverage and reliability in a confined operational context [25]. Kenya’s standard gauge railway integrates modern signaling, computer-based interlocking, GSM-R communication, and IP-based transmission networks to support centralized traffic control [26]. Slovenia operates a mixed analog–digital dispatching environment, where Ethernet-connected digital dispatcher consoles coexist with analog field devices and GSM-R-based mobile communication on main corridors, while regional lines retain predominantly analog solutions [27].

Hybrid communication and dispatching architectures are also reported outside Europe. In Japan, integrated 5G–TETRA solutions combine narrow-band mission-critical voice services with broadband data communication to support real-time monitoring and advanced train operations during transitional phases [28]. In China, the vast infrastructure of high-speed rail has come with the development of digitalization of railway dispatching systems, including highly centralized traffic dispatching command systems to implement real-time train supervision, timetable control, signaling coordination, and communication services in unified software environments [16]. These examples demonstrate that dispatching-system modernization is typically incremental and context-dependent, shaped by legacy infrastructure, regulatory constraints, and operational priorities rather than by the adoption of a single communication technology.

Serbia represents a particularly illustrative example of this transitional landscape. Within the national railway network, legacy analog dispatcher telephony, radio communication based on Union Internationale des Chemins de fer (UIC) tone signaling, and

long-established trackside equipment remain operationally essential, while optical fiber transmission, digital dispatcher centers, and IP-based multi-service networks are being progressively deployed. In parallel, mobile communication systems such as GSM-R are introduced within the broader ERTMS framework. This coexistence of analog, hybrid, and digital technologies underscores the need for dispatching architectures that explicitly support backward compatibility, interface preservation, and scalable integration across fixed-line and radio communication domains. These requirements directly motivate the design principles and integrated dispatching architecture presented in this paper, which address dispatching-system evolution independently of the specific communication technology employed.

3. Research Methodology

This study adopts a design-oriented, system-level research methodology to investigate the digital transformation of railway dispatching systems under real operational constraints. Rather than evaluating isolated algorithms or components, the methodology focuses on the analysis of an existing legacy dispatching system, the design of an incremental migration architecture, and the operational validation of hybrid analog–digital coexistence within a critical railway environment.

This approach is motivated by the characteristics of railway dispatching systems, which are large-scale, long-lived socio-technical systems where experimental replacement or laboratory-based evaluation is neither feasible nor permissible. Consequently, the research contribution is derived from the systematic analysis, redesign, and deployment of an operational architecture, combined with the abstraction of transferable principles.

3.1. Legacy Dispatching System as the Baseline for Methodological Analysis

The analog dispatching system of Serbian Railways represents one of the most enduring and operationally significant components of the national railway telecommunication network. Established in the mid-twentieth century and progressively upgraded through the 1980s and 1990s, it formed the backbone of operational communication between railway personnel. The system comprised both wired and radio subsystems—namely the trackside dispatching network and the radio-dispatching network, respectively.

Despite their functional alignment, the trackside dispatching and radio-dispatching systems were not based on a shared infrastructure. The trackside subsystem relied on dedicated two- or four-wire copper circuits that provided base-band links between the dispatcher console and trackside telephones, and was used exclusively for operational voice communication between central traffic dispatchers and station control personnel. Trackside telephones are referred to as Universal Trackside Telephones (UTT) because they can be deployed in multiple operational configurations and installed at various locations along the railway line, including track sections, signaling points and other infrastructure elements.

On the other hand, the radio-dispatching subsystem relied on trackside base stations (TBS) that provided radio communication between central traffic dispatchers and train drivers. Thus, the radio-dispatching subsystem incorporated an additional Radio Frequency (RF) layer built around geographically distributed TBS units, converting base-band voice and signaling tones into the RF band for locomotive radio communication and enabling reliable long-distance voice and signaling communication using audio-frequency signaling tones (often referred to as “telegrams”), as defined in UIC 751-3 [29]. The dispatcher console was connected to a TBS via a four-wire copper circuit for full-duplex communication. This made the radio subsystem a transparent extension of the wired network, bridging dispatcher–TBS communication (wired) and TBS–locomotive communication (radio). Radio coverage was achieved through directional or omnidirectional

antennas, ensuring continuous dispatcher–train communication across the relevant dispatching sections. Functionally, dispatchers could initiate selective or group calls and receive locomotive-initiated calls while monitoring connection status and line integrity on the console. Wireline–radio coupling enabled the establishment of conference calls involving train drivers, dispatchers, and external telephony endpoints when required for operational coordination.

As the primary device for recording and archiving dispatcher communications, the so-called registrophone was used, ensuring operational accountability and traceability of voice exchanges across both wired and radio channels in compliance with railway communication procedures. Recordings were initiated automatically upon line activation or by dispatcher command. However, the device lacked integration with dispatcher consoles or signaling equipment and provided no digital indexing or remote access capabilities. Consequently, the retrieval of specific records required manual playback and interpretation. Nevertheless, the registrophone played a critical role in post-incident analysis and regulatory compliance and provided the conceptual basis for digital call-logging subsystems.

Despite its analog nature, the system demonstrated exceptional operational stability and resilience. Redundant copper circuits, passive elements, and TBS site configurations enabled uninterrupted coordination even under degraded transmission conditions or power-supply disturbances. It also ensured a minimum level of communication traceability and accountability and laid the foundation for the subsequent modernization and digital transformation of Serbian Railways, serving as a precursor to modern digital recording and archiving systems, including the CCRMAS described in this paper [30].

This legacy system therefore, provided not only a functional baseline but also a methodological reference point for modernization, defining the operational behaviors and reliability characteristics that had to be preserved.

3.2. Methodological Principles for Incremental Modernization

Within this methodological framework, the modernization of the railway communication network represents a key step in aligning national transport infrastructure with European interoperability standards [31] and broader digital-transformation objectives.

Based on the analysis of the legacy dispatching system, the modernization methodology was defined around the principle of incremental migration. Instead of full replacement, the approach introduces digital subsystems that interoperate transparently with existing analog infrastructure, ensuring uninterrupted operation and preserving established dispatcher workflows.

A central aspect of this methodology is the replacement of the physical transmission medium without altering service behavior. Copper circuits are progressively replaced by optical fiber links using analog–optical converters, preserving legacy signaling and voice characteristics while significantly improving transmission quality, availability, and noise immunity. This transition enables multiple dispatching and control services to be carried over a unified, high-capacity transmission infrastructure.

At the same time, dispatching functionality is progressively decoupled from dedicated hardware and relocated into software-based services. Dispatcher consoles, media converters, telephony gateways, and auxiliary communication devices are interconnected through an enterprise IP network, allowing dynamic routing, centralized supervision, and flexible reconfiguration. Crucially, legacy signaling tones, interfaces, and operational semantics are preserved at system boundaries, enabling analog trackside and radio equipment to coexist with a LAN (Local Area Network)-based, software-centric core.

3.3. Interface-Level Adaptation and Hybrid Integration

Rather than redesigning field equipment or dispatcher procedures, the methodology relies on interface-level adaptation as the primary integration mechanism. Analog electrical interfaces, UIC tone signaling, and procedural workflows remain unchanged, while internal system logic is re-implemented using digital signal processing, VoIP transport, and software-controlled call handling.

This approach enables newly developed digital components to coexist with older devices without altering their external behavior. It ensures functional continuity while introducing capabilities such as centralized supervision, redundancy management, selective call handling, and scalable expansion. Optional interconnection with other railway telephony systems, such as the Railway Internal Telephone Network (RITN), is supported without compromising backward compatibility.

3.4. System-Level Validation and Archiving Integration

Because controlled experimental evaluation is not feasible in operational railway environments, validation is performed at the system level, focusing on functional equivalence, operational continuity, and traceability. The legacy requirement for continuous recording and accountability directly informed the design of the CCRMAS.

The CCRMAS transforms the concept of the registraphone into a distributed, software-based service that performs automated acquisition, integrity verification, and centralized indexing of dispatcher voice records and operational command/notification messages. Recording tasks are distributed across software-defined components, while authenticity and integrity checks are applied prior to database storage. This design preserves the traceability principles of the legacy system while enabling secure, searchable, and auditable digital archiving.

A practical example is the reconstruction of the Belgrade–Novi Sad high-speed railway, where the optical network now serves as the primary transmission medium for numerous subsystems, including radio–dispatcher links, centralized traffic control, level-crossing supervision, and signaling control. In addition, a redundant optical fiber ring topology ensures fault tolerance and high availability. Similar design practices were adopted on the Novi Sad–Subotica section. The adoption of optical infrastructure not only enhanced communication quality and reliability but also established a scalable foundation on which additional IP-based services, such as network monitoring, data logging, and distributed control, can be deployed without additional physical cabling.

3.5. Abstraction and Transferability

Although the methodology is grounded in the Serbian railway context, it explicitly incorporates an abstraction step. System-specific implementation details are generalized into transferable principles addressing incremental migration of critical communication systems, coexistence of analog and digital infrastructure, unified archiving across heterogeneous domains, and long-term scalability under regulatory constraints.

3.6. Evaluation Framework and Metrics

Given the critical and operational nature of railway dispatching systems, controlled experimental evaluation or randomized testing is not permissible. Therefore, the system is evaluated using a design-oriented, system-level validation framework based on three complementary dimensions:

1. Functional Equivalence and Continuity: Verification that legacy operational behaviors, signaling semantics, and dispatcher workflows remain unchanged during migration.

2. Quantitative Communication Performance Indicators: Objective network- and transport-layer metrics derived from RTP/RTCP (Real-time Transport Protocol/Real-time Transport Control Protocol) monitoring, including latency, jitter, packet loss, and derived media quality indicators.
3. Traceability and Integrity Metrics: Verification of recording completeness, cryptographic integrity checks, time synchronization consistency, and archival durability under operational load.

These metrics are collected during live operation and interpreted against accepted thresholds for mission-critical voice communication systems.

4. Digital Railway Dispatching Communication Architecture with Centralized Call Records and Messages Archiving

The ongoing modernization of the national railway communication network has brought together three, formerly separate, systems into a cohesive architecture: the RDCS, the DRDS, and the CCRMAS. Within this unified digital operational framework, RDCS supports fixed-line communication with stations and trackside personnel, while DRDS extends identical operational logic to mobile units (locomotives and other railway vehicles) via radio connectivity, complemented by a dedicated control and notification layer. The CCRMAS serves as the shared voice records, commands, and notifications messages archiving service for both subsystems, ensuring consistent capture, verification, and long-term preservation of all operational communication. Together, these subsystems form an integrated platform that enhances safety oversight, improves interoperability, and reinforces regulatory compliance across the national railway network.

In addition to these dispatching subsystems, the RITN remains an integral component of the national railway communication environment. It is a dedicated private Public Switched Telephone Network (POTS)/Plain Old Telephone Service (PSTN) system used exclusively for internal operational and administrative telephony. Through standardized signaling interfaces and gateway modules, the RITN interconnects with both the RDCS and DRDS, enabling dispatchers to communicate with station offices, maintenance units, and other operational departments. This integration ensures continuity of internal telephony services during the transition toward a fully digital architecture.

Accurate time synchronization is ensured through a hierarchical Network Time Protocol (NTP) infrastructure deployed across the railway network. Each station hosts a Stratum-1 NTP server synchronized to a Stratum-0 high-precision time source, providing a reliable timing reference independent of external networks. All local servers, dispatcher consoles, communication nodes, and CCRMAS components synchronize to the station's Stratum-1 server, ensuring consistent timestamps for call records, event logs, diagnostics, and system supervision. This unified timing architecture is essential for post-incident analysis, operational traceability, and the coordinated functioning of distributed digital subsystems.

Figure 1 illustrates the logical architecture of the integrated dispatching system and the overall integration of the RDCS, DRDS and CCRMAS components. Both the RDCS and DRDS are connected to a unified IP-routed optical backbone. Each dispatcher console interfaces with the VoIP servers responsible for session management, while all call and control streams are continuously persisted by the CCRMAS. The CCRMAS subsystem acts as a shared layer, providing real-time verification, recording, archiving, and event records indexing for both wired and wireless communication domains. System resiliency is provided through redundant servers and storage elements and dual fiber optic network paths.

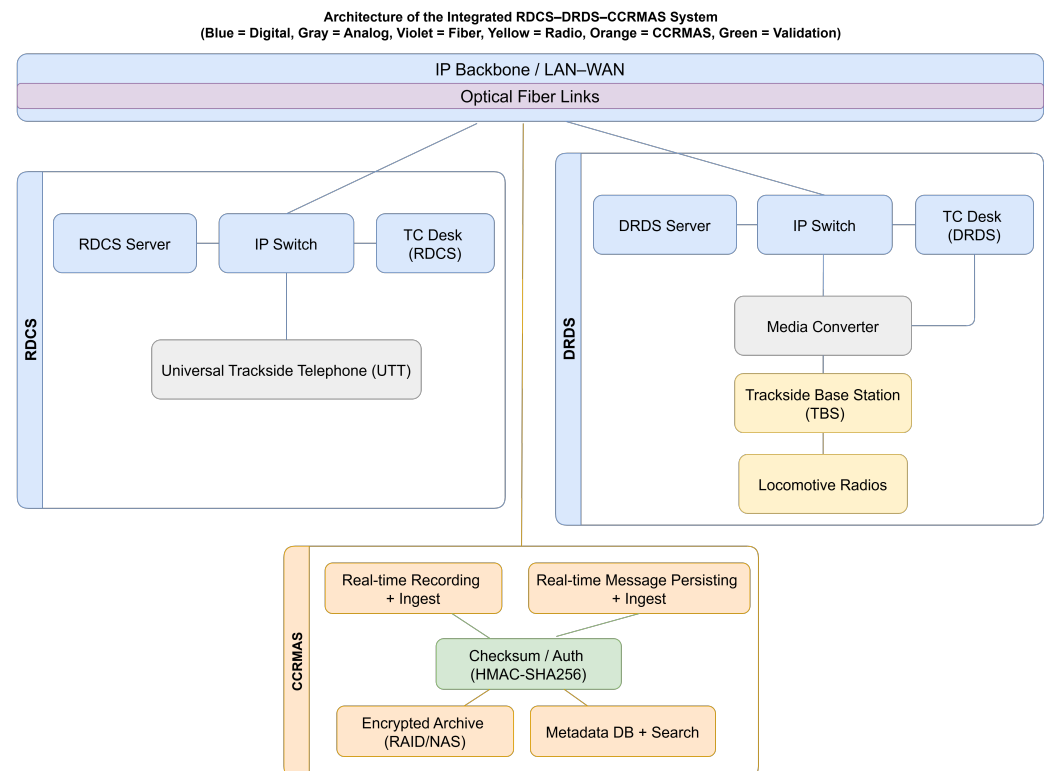


Figure 1. Conceptual architecture of the integrated RDCS–DRDS–CCRMAS system, illustrating the separation between legacy analog dispatching endpoints and the software-enabled IP core, as well as the centralized role of CCRMAS in unified voice and command/message archiving across fixed-line and radio-dispatching domains.

For smooth integration with legacy equipment, specialized devices were developed to transparently bridge different communication domains. Where analog and digital networks must coexist, dedicated converters were used to achieve full bidirectional signal transparency. To ensure compatibility with new digital transmission technologies without risking vendor lock-in, integration of legacy systems was carried out using open, standardized protocols.

The presented architecture focuses on dispatcher communication handling, supervision, and archival functions; while it interfaces with existing railway operational environments, it does not perform traffic regulation, route setting, train control, or decision-making typically associated with centralized traffic control systems. Such functions remain outside the scope of this work and continue to be handled by dedicated signaling and control subsystems.

Discussion and Evaluation. From an evaluation perspective, the integrated dispatching architecture was assessed against system-level criteria of functional equivalence, operational continuity, reliability, traceability, and scalability, as defined in Section 3.6. Across both fixed-line and radio-dispatching domains, legacy operational behavior—including dispatcher workflows, signaling semantics, selective calling procedures, and field-device interfaces—was preserved without modification, while communication handling, supervision, and recording functions were migrated to a software-centric IP core. No changes to dispatcher or train-driver operating procedures were required, satisfying the functional equivalence criterion. The separation between legacy endpoints and the IP-based core enabled effective post-event tracing. High availability and scalability were achieved through pools of functionally equivalent VoIP servers with client-side server selection, allowing transparent fail-over and incremental capacity expansion without dispatcher intervention. In parallel, the CCRMAS replaced the legacy registraphone by providing continuous, automated, and integrity-verified recording of dispatcher voice communication and structured

command and notification messages across heterogeneous wired and radio domains. Cryptographic integrity checks, synchronized time-stamping, and centralized indexing ensured end-to-end traceability, auditability, and cross-domain correlation of operational records, exceeding the capabilities of analog recording solutions.

4.1. Railway Dispatching Central System

The RDCS (Figure 2) constitutes an essential element of the modernized fixed-line dispatcher communication architecture. It was developed to replace the legacy analog trackside dispatching centers previously deployed across the national railway network, thereby enabling structured and reliable communication between central traffic control dispatchers, station operators, and personnel located at operationally critical sites such as level crossings, signal posts, and trackside technical facilities. Furthermore, the system was designed to remain compatible with legacy protocol families, ensuring continued interoperability with existing field equipment, such as analog UTTs (A-UTT) [32]. Where optical fiber infrastructure has been implemented, newly designed digital UTTs (D-UTT) have been installed. Accordingly, the RDCS supports both newly deployed digital endpoints and existing analog devices, ensuring functional continuity across non-digitalized sections of the network.

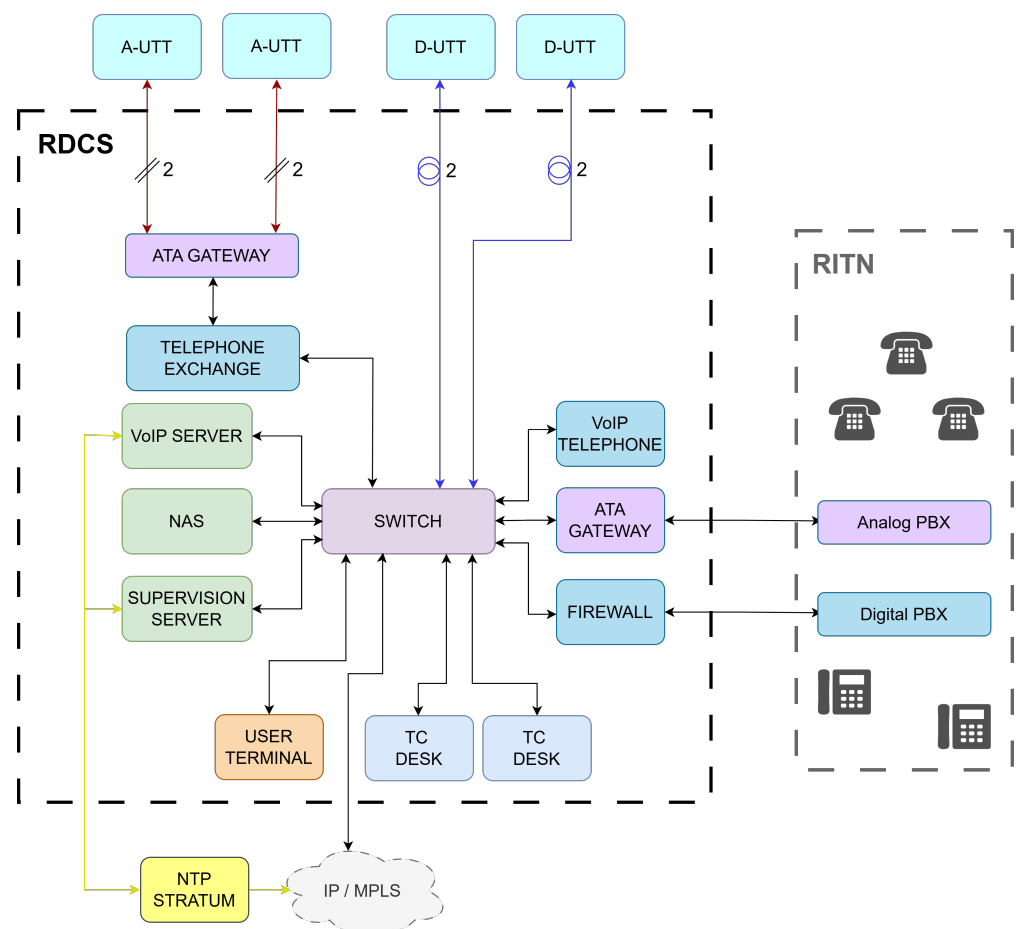


Figure 2. Architecture of the Railway Dispatching Central System (RDCS) system, showing how legacy analog trackside telephones and digital endpoints are integrated through a software-centric core that preserves established dispatcher workflows while enabling centralized control, supervision, and VoIP-based communication.

The RDCS consists of a central equipment unit and a set of peripheral devices. The central unit, installed in dedicated telecommunication rooms, integrates several essential

components. These include core servers that manage network services, coordinate system processes, and facilitate information exchange among system elements, as well as VoIP servers that establish, terminate, and monitor calls between dispatcher terminals and trackside endpoints. The central unit also incorporates switching elements that aggregate external optical connections and integrate IP-based telephony devices into the system network. In addition, it includes PSTN/RITN gateways enabling access to public and railway analog telephony, together with an NTP service that ensures accurate time synchronization.

Peripheral devices deployed in the operational environment comprise TC desks serving as the primary human–machine interface for call handling and command execution, auxiliary telephones enabling fallback communication in cases of console malfunction, and train-arrival notification devices such as bells or loudspeakers. The peripheral subsystem also includes a user terminal that offers command-line access to network elements and servers, supports the management and supervision of core operational functions, and provides access to the CCRMAS web interface.

All system components are interconnected through a LAN-based architecture that supports scalability, the distributed placement of user terminals, and the integration of auxiliary equipment, including public-address amplifiers and auxiliary telephones. From an operational perspective, the RDCS forms a unified telecommunication layer for all trackside facilities. It consolidates connections to trunk and local cable networks, traffic and traction dispatching subsystems, legacy RITN telephony, and VoIP services, thereby reducing the fragmentation characteristic of earlier telecommunication infrastructures and establishing a coherent digital environment capable of supporting advanced monitoring, diagnostics, and automation functionalities.

Pool of VoIP Servers

All VoIP servers within the RDCS are functionally equivalent and operate without a designated master or standby role. High availability is achieved through client-side server selection rather than centralized call-control failover. Each client is configured with an ordered list of available VoIP servers. Under normal operation, the client establishes signaling and media sessions with the first server in the list. If the selected server is unavailable or becomes unreachable, the client automatically attempts to connect to the next server in the predefined order, continuing until a successful connection is established.

This distributed server-selection mechanism eliminates single points of failure at the call-control level and enables seamless continuation of dispatcher communication in the presence of individual server outages. Because server equivalence is preserved, additional VoIP servers can be introduced into the pool without modifying dispatcher workflows or endpoint configuration logic, supporting incremental scalability and simplified maintenance.

A high level of customization required by the Serbian railway system led to the selection of Asterisk [33] as the most suitable platform among a wide range of available IP Private Branch Exchange (PBX) solutions, extending from proprietary hardware appliances to open-source software. With more than twenty-five years of development, Asterisk is regarded as a mature open-source platform, characterized by reliability, extensive testing, and strong community support.

One of its principal advantages is the possibility for highly sophisticated dial plans to be implemented through the Lua scripting language. By using Lua and the Asterisk Application Programming Interface (API), custom databases can be accessed and modified, and Session Initiation Protocol (SIP) [34] signaling can be extended through the introduction of additional protocol headers. These custom headers enable the conveyance of enriched endpoint information, such as a “line” connection, that is not supported by standard SIP implementations. However, this capability requires the development of custom SIP

endpoints, since many commercial SIP clients do not permit the reading or modification of non-standard SIP headers.

In addition to SIP-based signaling, Asterisk relies on the RTP protocol [35] for the transport of real-time media streams such as voice and video. RTP operates over UDP (User Datagram Protocol) to minimize latency and provides mechanisms, including sequence numbering and timestamping, which are essential for proper media synchronization and loss detection. Within Asterisk, RTP streams can be monitored in real time, enabling the system to collect low-level transmission metrics. These metrics form the basis for the calculation of the Media Experience Score (MES), an internal parameter that reflects the perceived quality of a media session from an end-user perspective.

The RTCP protocol [35] complements RTP by periodically exchanging control information related to media delivery performance, such as packet loss, jitter, and round-trip delay. Asterisk leverages RTCP reports to compute and continuously update the MES during active calls. By aggregating RTP and RTCP statistics, MES provides a quantitative indicator of call quality that can be used for monitoring, diagnostics, and decision-making within higher-level applications. This capability enables Asterisk-based systems to detect media degradation in real time and supports adaptive behaviors, such as alerting, call rerouting, or quality-based analytics, thereby enhancing overall VoIP service reliability.

Through the use of Asterisk and the deployment of customized SIP clients, the operational behavior of the legacy telephony network has been successfully replicated, while new functionalities and opportunities for future system evolution have been enabled.

4.2. Telecommunication Console and User Interface

The Telecommunication Console (TC desk) provides operators with a unified environment for managing communication across different subsystems. Its design emphasizes clear interaction, rapid response, and reliability, combining a touch-enabled display with familiar physical controls to support time-critical work. By visually and functionally echoing legacy equipment, the interface eases user transition and reduces the potential for operational errors.

Behind the scenes, the TC desk uses a streamlined and tightly controlled software environment that exposes only the operator application, supporting both security and high availability. The system's configuration is fully externalized, allowing simple adaptation to different operational roles (e.g., RDCS vs. DRDS) without hardware changes.

The TC desk manages communication through multiple servers, automatically switching to backups during outages and returning to the primary server once it is available. The server selection logic is entirely transparent to dispatchers and does not require manual intervention during failover events, ensuring continuity of operational communication. TC desk design also preserves compatibility with legacy operational practices, ensuring that established workflows and line management conventions are maintained while supporting modern communication methods.

4.3. Digital Radio-Dispatching System

The DRDS, shown in Figure 3, extends the dispatcher communication domain from fixed points to mobile railway units, providing continuous connectivity with moving trains and enabling the transmission of dispatcher commands to locomotive on-board systems, as well as the exchange of train-driver-generated notifications. The system retains the functionalities of the analog radio-dispatching infrastructure by introducing digital transmission, full-duplex communication, and selective calling within predefined frequency bands, thereby enhancing operational reliability and communication clarity.

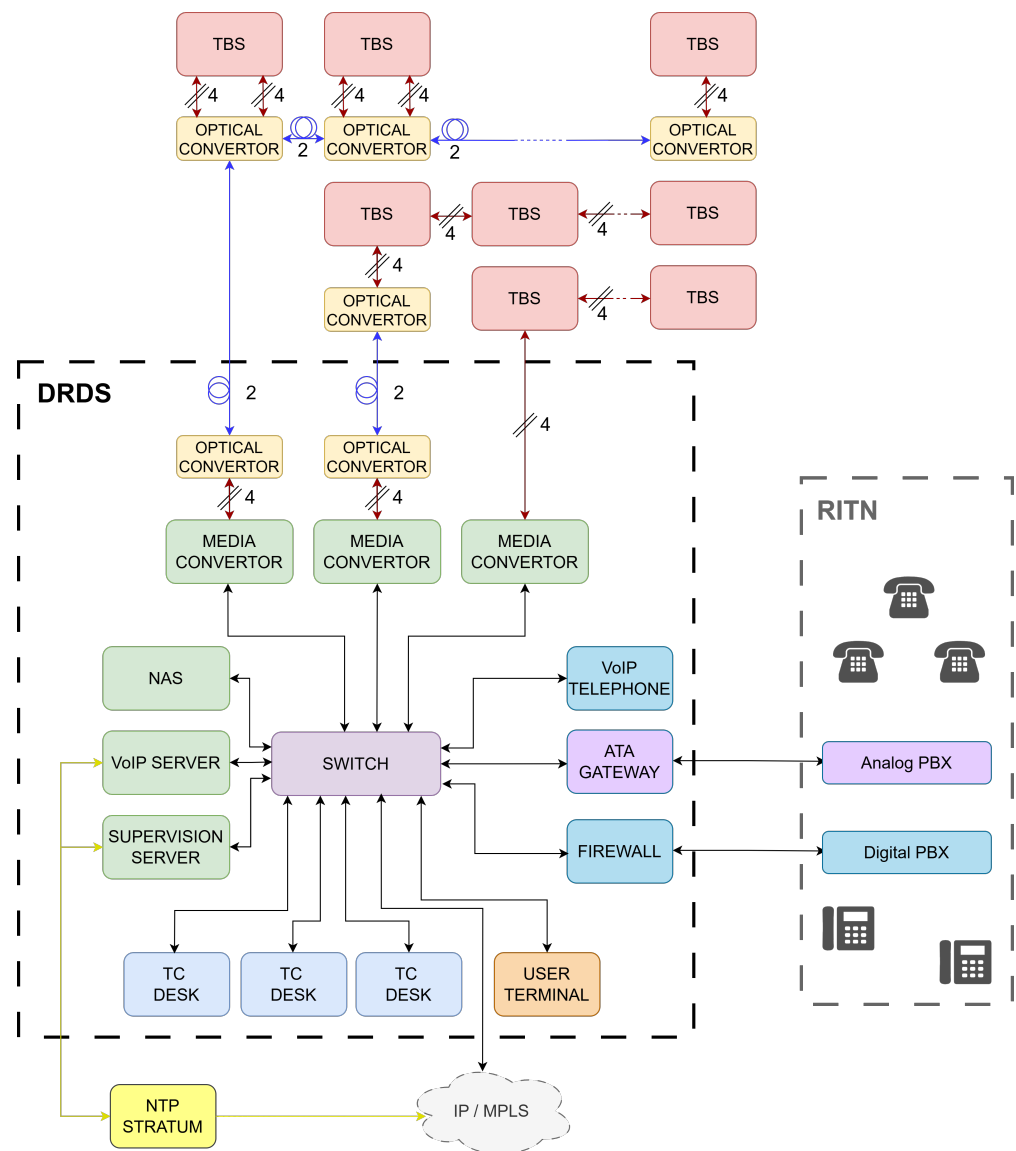


Figure 3. Digital Radio-Dispatching System (DRDS) architecture, highlighting interface-level adaptation between legacy UIC tone-based radio signaling and the IP-based dispatching core, enabling full-duplex communication, selective calling, and centralized supervision without altering legacy radio equipment used for train–ground communication.

The DRDS architecture comprises dispatcher TC desks, central servers, VoIP servers, media converters equipped with UIC 751-3 interfaces, and user terminals. As in the RDCS subsystem, all VoIP servers within the DRDS are functionally equivalent, and dispatcher TC desks select a server from an ordered list, ensuring transparent server selection without affecting dispatcher workflows. Communication is facilitated through TBSs, which are connected to the dispatching center via optical or copper links. Each TBS serves as a bridge between wired and wireless networks, retransmitting dispatcher messages to locomotive-mounted transceivers. The system supports duplex and simplex modes, selective call addressing, group (broadcast) calls, and emergency signaling initiated by either the dispatcher or the locomotive.

Digitalization enhances analog audio transmission through the adoption of VoIP, improving signal clarity and reducing latency. Automatic link supervision ensures communication reliability, while interoperability with legacy radio equipment is maintained through protocol adaptation mechanisms. Operational control relies on a predefined set of commands and notifications, transmitted as structured digital messages, commonly referred to as telegrams, using frequency-shift keying (FSK). Each message adheres to a defined format, enabling unambiguous identification and verification:

<START><UNIQUE_TRAIN_ID><COMMAND><CRC>

All transmitted messages are logged, stored, and archived via the CCRMAS, ensuring comprehensive traceability and supporting post-event analysis. This approach provides a robust framework for operational oversight, safety management, and accountability, while enabling the gradual transition from analog to fully digital railway communication systems.

TC Desk DRDS Specific Functionality

Beyond the capabilities described earlier, the TC desk, when deployed in the DRDS subsystem, is configured to communicate with a dedicated media converter that operates under its own SIP extension. The media converter performs real-time audio conversion between SIP VoIP (toward the TC desk) and analog radio (toward the locomotive), enabling reliable dispatcher–train driver communication within the assigned track section.

In addition to voice communication, the operator application exchanges operational commands and notifications with the media converter (e.g., immediate stop, drive faster, drive slower) over a persistent Transmission Control Protocol (TCP) connection. Commands and notifications originating from the train are delivered to the TC desk through the same connection, ensuring low latency without per-command connection setup.

4.4. Call Recording and Archiving

A significant component of the integrated dispatching architecture is the CCRMAS—a software-defined subsystem responsible for recording, validating, and storing all communication across both RDCS and DRDS networks. The CCRMAS replaces the traditional registraphone hardware, distributing its functionality across VoIP servers, a centralized archival server, and a web-based user interface (UI).

The CCRMAS's predecessor, the Centralized Call Recording and Archiving System (CCRAS) [30], was a component of the RDCS in the first iteration. It included at least one VoIP server, an archival server, and a web application. A block diagram of the system is shown in Figure 4.

The reliability of data storage and the authenticity (origin verification) of each data entry are critical. Data transfer integrity and recording authenticity are ensured through multiple security measures. The Hash-Based Message Authentication Code using the Secure Hash Algorithm 256-bit (HMAC-SHA256) cryptographic technique is used for data record “signing”, a secure file transfer protocol protects records during system transfers, and the applied Atomicity, Consistency, Isolation and Durability (ACID) consistency model guarantees data accuracy.

4.4.1. CCRAS System Architecture

The Call Record Archive Server provides the redundancy required for secure data retention. Access to archived records is provided through a web-based application that serves as the user interface of the CCRAS system. The application processes user requests and enables authorized personnel to search, view metadata, and listen to recorded calls.

The archived call list is consolidated: audio recordings from all servers are shown on the same page.

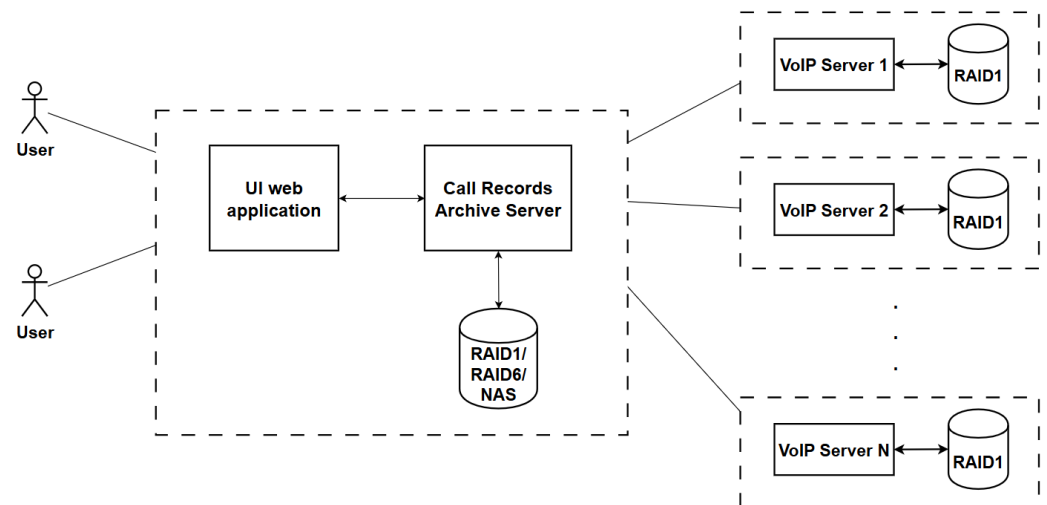


Figure 4. Architecture of the Centralized Call Recording and Archiving System (CCRAS), showing distributed acquisition of voice records from VoIP servers, centralized integrity verification, indexing, and long-term storage to support auditability and post-event analysis. CCRAS is the predecessor of the Centralized Call Record- and Message-Archiving System (CCRMAS).

4.4.2. Security Architecture

The security architecture of the CCRAS is designed to ensure authenticity, integrity, durability, controlled accessibility, and governance compliance of dispatcher communication records across both RDCS and DRDS subsystems. As a software-enabled successor of the legacy registrophone, CCRAS distributes acquisition, verification, archival persistence, and user access across logically separated components while preserving evidentiary guarantees required in railway operational environments.

Integrity and Origin Authentication

Authenticity and integrity of recorded communication are enforced at the point of acquisition. Each voice record is cryptographically protected using a Hash-Based Message Authentication Code (HMAC) constructed with the Secure Hash Algorithm 256-bit (SHA256). The HMAC is generated on the VoIP server immediately after recording creation, binding the audio content to a server-specific secret key.

Upon transfer to the centralized archive server, the HMAC value is recomputed using the shared secret key and verified prior to database persistence. Any mismatch results in classification of the record as integrity-unverified.

This mechanism ensures the integrity and authenticity of records by facilitating the detection of unauthorized modifications, enabling verification of the record origin through proof of possession of the symmetric secret key, and mitigating the risk of silent corruption during storage or transmission.

Secure Data Transfer and Transactional Consistency

All communication records are transferred from distributed VoIP servers to the centralized archive server using Secure File Transfer Protocol (SFTP), ensuring encrypted transport across the IP backbone and protection against interception or manipulation during transmission.

Archival persistence follows an ACID consistency model. The transfer and ingestion process is structured as a transactional workflow in which integrity verification, metadata

extraction, database insertion, and storage operations are executed atomically. If any stage fails, the transaction is rolled back to prevent partial or inconsistent archival states.

This design guarantees that incomplete or corrupted files are never persisted, that metadata and audio records remain consistently synchronized, and that the database contains only complete archival records.

Redundant and Durable Storage

Long-term retention and durability of dispatcher communication records are ensured through storage redundancy mechanisms implemented at the Call Record Archive Server level. Two alternative redundancy strategies are supported:

- By employing appropriate Redundant Array of Independent Disk (RAID) technology, which combines several physical disks into a single logical unit to ensure the necessary redundancy for data protection. RAID6 is preferred, but RAID1 can also be used with more than two disks.
- By utilizing a mount-point, supported by industrial-grade physical Network-Attached Storage (NAS). A NAS device is recommended for the system due to its ease of expansion and increased flexibility.

These mechanisms protect against single-disk failures and enable scalable storage expansion without architectural modification. The redundancy model supports regulatory retention requirements and evidentiary preservation.

Key Management

Each VoIP server is provisioned with a unique symmetric HMAC-SHA256 key during secure system initialization. The key is stored in an encrypted configuration file accessible only to the VoIP service process. The central archiving server maintains an encrypted key store that maps server identities to their corresponding keys for verification purposes.

During archival ingestion, the archive server retrieves the appropriate key based on the originating server identity and recomputes the HMAC to validate authenticity. Key rotation is supported by design via controlled re-provisioning procedures when required.

Threat Models

The primary threat model assumes an attacker who gains access to the IP network but does not possess the pre-shared HMAC keys. Under this model, any tampering with recorded audio files during transfer or while at rest will be detected during HMAC verification. Encrypted transport further mitigates interception risks.

If a VoIP server were compromised, its associated symmetric key could be exposed, potentially allowing an attacker to forge records originating from that specific server. To mitigate this risk, physical access controls and operating system security hardening are enforced at each VoIP and archive node. Server isolation, restricted service privileges, and monitored administrative access form part of the operational security posture.

Governance and Access Control

Access to the CCRMAS web interface is governed by a Role-Based Access Control (RBAC) model. Users are assigned predefined roles corresponding to their operational responsibilities (e.g., dispatcher, supervisor, system administrator, investigator). Each role defines a bounded set of permissions, including playback of recordings, metadata retrieval, audio download, and (where policy permits) record deletion.

Permissions are enforced at the application layer and validated on each request to prevent privilege escalation. Role assignments are managed by authorized administrative personnel and follow internal railway governance procedures. The principle of least

privilege is applied, ensuring that users are granted only the minimum access necessary to perform their duties.

All user actions performed within the system, including playback, download, meta-data access, and deletion, are recorded in a secure audit trail. Audit entries include user identity, timestamp (synchronized via NTP), action type, and target record identifier. This ensures traceability, accountability, and compliance with regulatory and organizational requirements for evidentiary data handling.

Physical access to critical dispatching and archival infrastructure is restricted to authorized personnel. The implemented access control mechanisms, together with the adopted data backup strategies, comply with national railway security regulations and the operator's internal infrastructure protection policies.

4.4.3. VoIP Server

The RDCS system utilizes VoIP servers to provide voice services. These VoIP servers facilitate communication between the VoIP entities, i.e., components capable of using VoIP for communication. The VoIP servers are configured to route all calls through the server, preventing direct communication between clients. This ensures that all calls are recorded on the VoIP server and are stored as audio files in WAV format (8 kHz/16 bit) in the file system on the VoIP server's local secondary memory, which also provides necessary redundancy for temporarily storing audio and control files. For each audio recording, the system tracks the originating system (RDCS or DRDS), a cryptographically generated identifier derived from the server's HMAC key, the caller identifier, the callee identifier, the trackside line identifier, and the Unix epoch timestamp (in seconds). Every audio file is accompanied by a corresponding checksum file containing an HMAC-SHA256 hash for verifying the file's origin and integrity.

HMAC key management is clarified at a system level: each VoIP server is provisioned with a symmetric authentication key during installation, and the archiving system stores this key in encrypted form alongside other sensitive configuration data.

4.4.4. Call Record Archive Server

The Call Record Archive Server manages the archive of audio recordings. Audio files serve as evidence in the event of a traffic accident or irregular situation, and the system must ensure that it adheres to the ACID data consistency model to maintain the integrity of both the audio file data and other data in the distributed system.

The Call Record Archive Server regularly checks the VoIP servers to identify new recordings that need to be archived. If new recordings are found, they are copied to a predefined directory ("mount-point") in the central secondary storage of the archive server (Central Call Record Storage—RAID1/RAID6, as shown in Figure 4) and the call record database is updated. The information needed to update the database is either embedded in the name of the retrieved file or can be determined from the file or the file transfer itself. The polling interval for each VoIP server is configurable (ranging from one second to one hour) and can be adjusted in real-time. Different VoIP servers may have different polling intervals.

The call record database stores information about all recordings that are currently archived. The HMAC-SHA256 hash, generated on the VoIP server, is one of the attributes of each audio file and is kept in the database. An audio file without an HMAC-SHA256 hash is considered invalid.

Audio files are transferred using the SFTP protocol. Once the audio file has been successfully copied and its HMAC-SHA256 checksum verified, the Call Record Archive Server removes the file from the VoIP server's local secondary memory to prevent re-

copying. Although it is not important for the end user which VoIP server the recording came from, the archive server keeps track of the VoIP server from which the audio archive was retrieved.

The software architecture of the Call Record Archive Server component is shown in Figure 5.

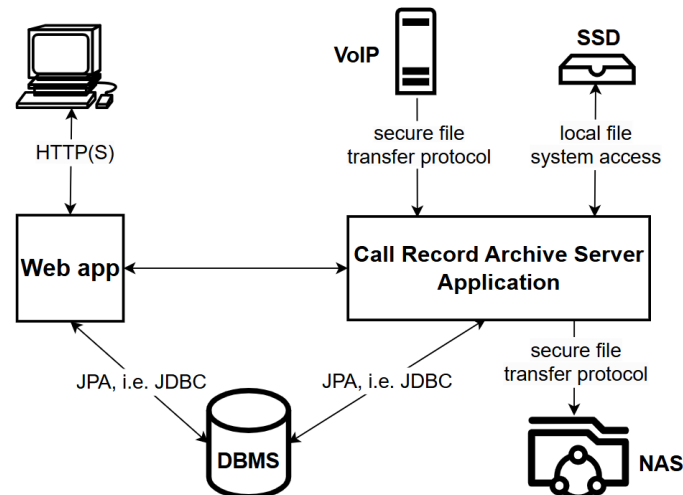


Figure 5. Software architecture of the Call Record Archive Server, showing modular components responsible for secure transfer, integrity verification, database persistence, and redundancy management within the centralized archiving workflow.

4.4.5. The Call Record-Archiving Process

The RDCS system consists of multiple VoIP servers, and the call record-archiving process collects recordings from all servers, ensuring that the ACID data consistency model is applied across the distributed system at every moment. VoIP servers are periodically checked at predefined intervals, and audio files are transferred to the archive server, where they are stored until their relevance period expires.

The call record-archiving process includes:

- Transferring the audio and control files from the VoIP server to the archive server;
- Processing the audio file on the archive server, which involves:
 - Checking the integrity of the audio file by comparing the checksums generated on both the VoIP server and the archive server;
 - Persisting the call recording information into the database;
 - Storing the audio file on the reliable redundant storage.
- Deleting the archived audio and control files from the VoIP server.

The archiving process is resilient and fault-tolerant by design, ensuring reliable recording and transfer of calls without data loss while guaranteeing the origin of the recordings.

Potential issues and limitations that could arise are:

- Transfer and processing of incomplete recordings: Neither the SFTP client, nor the Secure Copy Protocol (SCP) client, nor any other system process can determine if another process is accessing or modifying the file on the remote VoIP server or in the local secondary memory.
- Network problems, such as slow or unstable connections, disconnections, etc.
- Inaccessibility of system components, e.g., NAS, Database Management System (DBMS), VoIP server, etc.
- Possible data inconsistencies if the transfer and processing of audio and control files are not atomic.

To ensure the atomicity of audio recordings transfer and processing, as well as to minimize the risk of data loss, the archiving process has been designed and implemented as shown in Figure 6. This process is divided into atomic actions, or smaller tasks, that run independently. These tasks communicate via a database or an in-memory map that supports concurrent access. A transaction manager and publish–subscribe (observer) pattern are used to guarantee the atomicity of audio file transfers and processing.

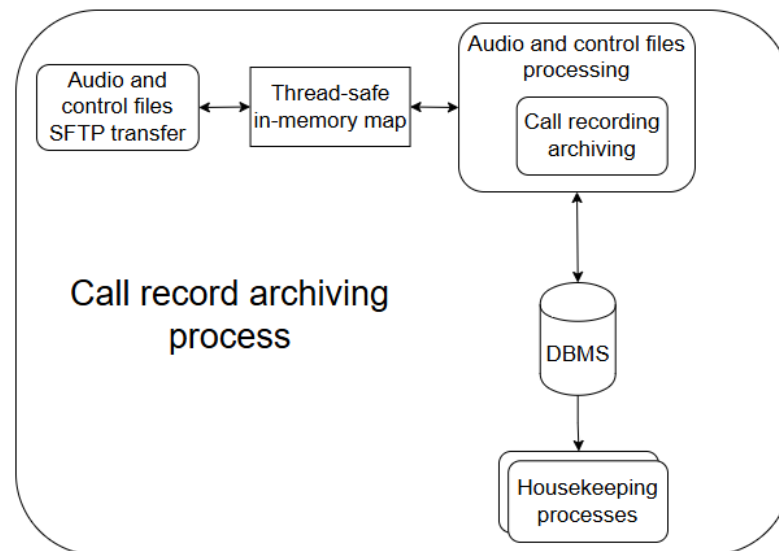


Figure 6. Call record-archiving process, illustrating the sequence of atomic actions used to ensure data integrity, consistency, and fault tolerance during acquisition, processing, and storage of dispatcher communication records.

The call record-archiving process includes the following tasks:

- SFTP Transfer of audio files and control sums;
- Processing the audio and control files with atomic persistence (archiving) of call recordings;
- Housekeeping processes that periodically delete transferred and processed files from the secondary memory of both the VoIP and archive servers, mark expired recordings for deletion and remove them.

The transfer process for audio files and checksums is shown in Figure 7. To prevent the transfer of incomplete files, a minimum waiting period is enforced, ensuring that a set duration passes after the file’s last modification before it becomes eligible for transfer. In Figure 7, this period is set to 5 min.

File integrity and authenticity are ensured using the HMAC-SHA256 cryptographic method, which employs a shared secret key in combination with the SHA-256 hash function to generate a message control code over the file contents. Upon reception, the archiving system recomputes the HMAC using the same secret key and compares it with the transmitted value. Any modification of the file results in a mismatching authentication code, while successful verification confirms that the file originated from an entity in possession of the shared secret key.

The audio and control file processing is shown in Figure 8. A Spring transaction manager is used to support atomic file processing. If a rollback occurs during a transaction, the Spring Framework transaction infrastructure, integrated with the Spring Event Listener framework, ensures that the rollback of the database data triggers additional actions, such as deleting files from secondary memory. A DBMS guarantees database consistency, while

the in-memory map (supporting concurrent access) is updated at the end of the transaction, after all other actions have been successfully completed. If a secure file transfer or file processing fails due to unexpected events, it will be retried several times. This ensures that file transfer, data ingestion, verification, persistence, and state updates are either completed consistently or rolled back entirely in the event of failure, preventing partial or inconsistent archival states.

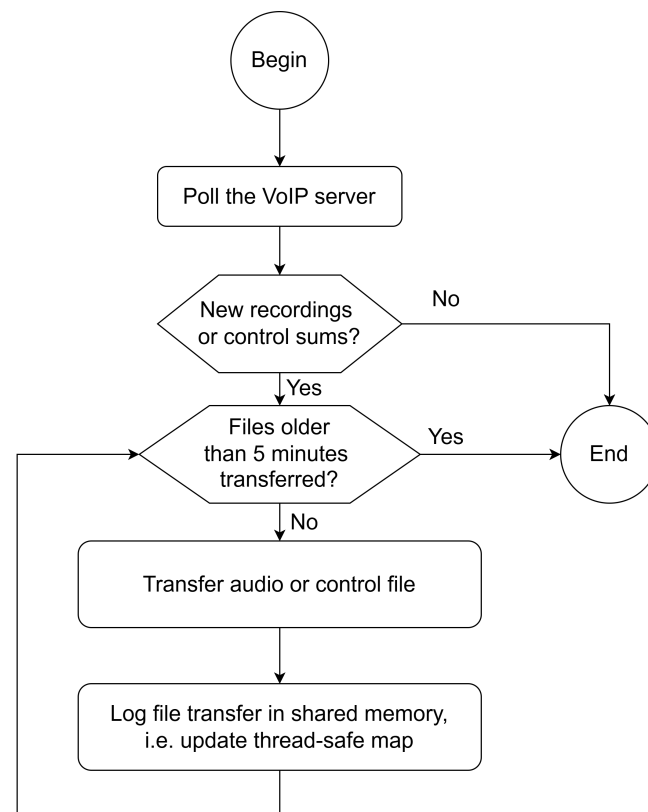


Figure 7. Secure file transfer procedure for dispatcher communication records, showing mechanisms used to prevent incomplete transfers and ensure authenticity and integrity prior to centralized archiving.

Housekeeping processes (shown in Figure 9) periodically check the database and delete transferred and recorded files from the secondary memory of the VoIP and archive server. The housekeeping process also periodically checks for recordings that have expired and marks them for deletion. Expired recordings are removed before the next check of recording relevance. Delaying file deletion helps prevent data loss in case of irregular situations.

4.5. Commands and Notification Messages Recording, Verification and Archiving

In the second iteration of the national railway network modernization, the CCRAS was extended beyond its original function of securely persisting dispatcher voice communication to also support the acquisition and archiving of command and notification within the DRDS system, as shown in Figure 10. This expansion was built upon the established framework for secure acquisition, verification, and long-term preservation of operational records, enabling the same integrity-assured mechanisms previously used exclusively for audio streams to be applied to digitally transmitted dispatcher instructions and notifications. As a result, the CCRMAS evolved from a voice-centric recording subsystem into a comprehensive integration layer for all relevant communication exchanged across the digital dispatching architecture.

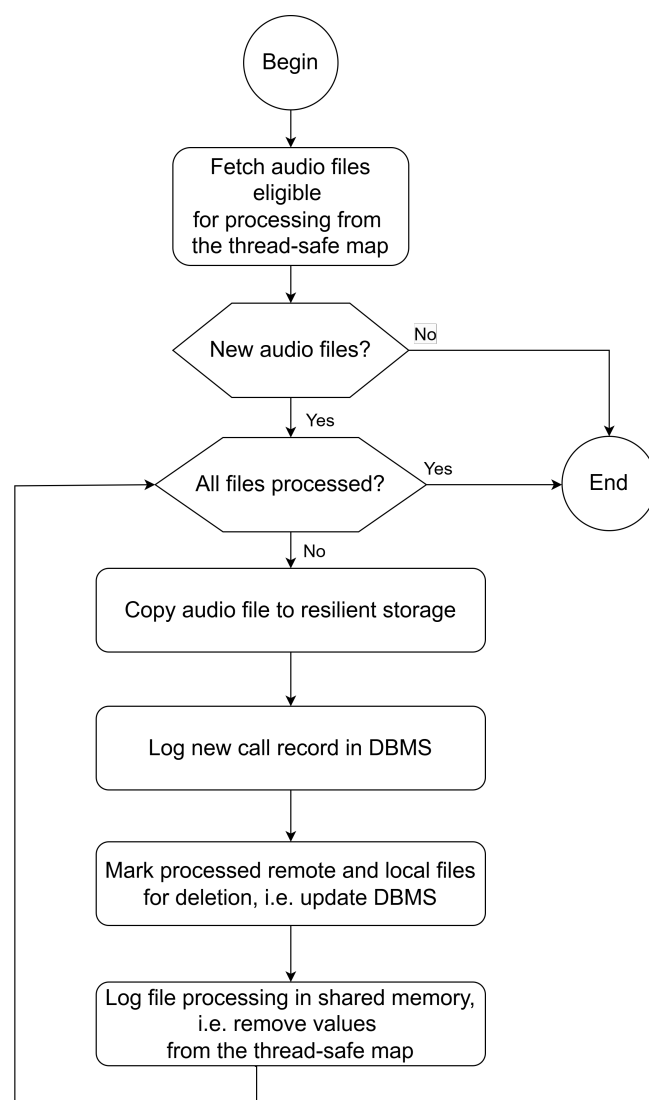


Figure 8. Processing workflow for audio and control files, demonstrating transactional handling and integrity validation used to guarantee atomic persistence of dispatcher communication records.

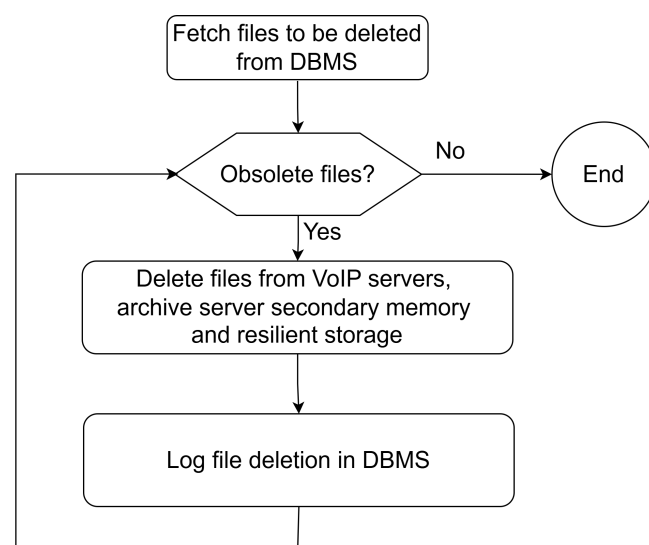


Figure 9. Housekeeping processes responsible for lifecycle management of archived communication records, including cleanup of temporary files, enforcement of retention policies, and prevention of data loss in irregular situations.

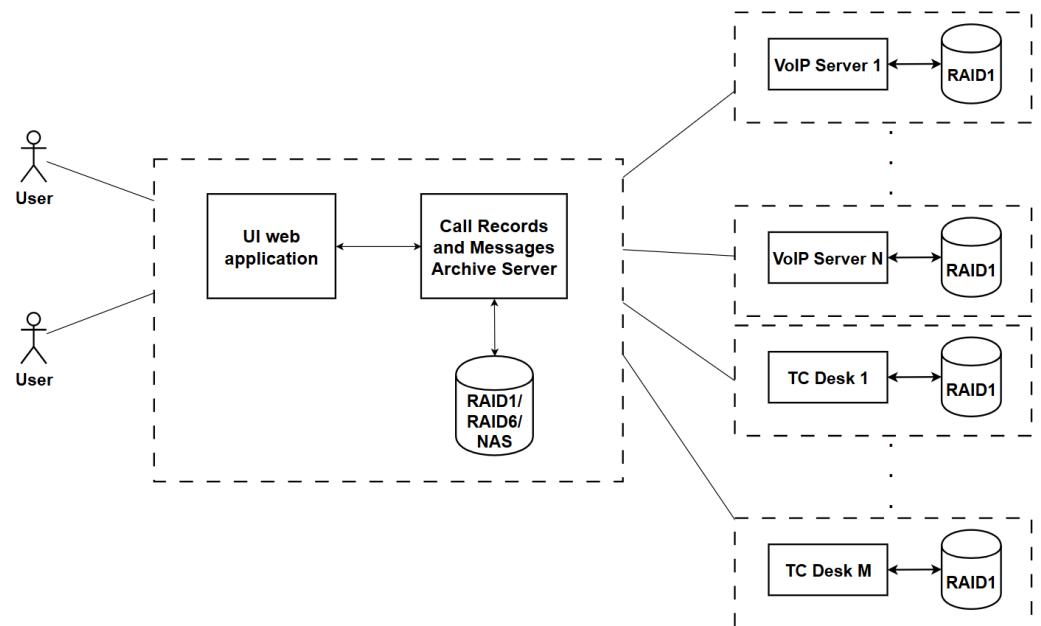


Figure 10. Centralized Call Record- and Message-Archiving System (CCRMAS) architecture, illustrating the integration of dispatcher command and notification message archiving with voice records, enabling unified traceability and correlation across digital radio and fixed-line dispatching domains.

The transfer procedure for command and notification messages mirrors the secure file-transport mechanism utilized for voice records. Messages are temporarily buffered on TC desks and periodically transmitted to the CCRMAS using secure SFTP channels, with automatic retry logic and transactional safeguards preventing loss during network disruptions. The CCRMAS processes incoming messages through the same verification pipeline that is applied to audio files: integrity validation, encryption, classification, and indexing within a relational database optimized for high-volume retrieval.

Long-term archiving of command and notification messages uses the identical redundancy model implemented for voice communication. RAID-protected storage, database-level replication, and optional off-site NAS devices ensure durability over regulatory retention periods. Because command and notification messages are typically lightweight, the CCRMAS can store years of operational history without impacting storage capacity reserved for audio archives. Integrated consistency checks allow correlation between a voice exchange and its associated command set, supporting post-event analysis, operational audits, and communication-related safety investigations.

By leveraging its mature set of voice-archiving algorithms and mechanisms, the CCRMAS provides a unified and verifiable framework for both audio and non-audio operational records. The extension of CCRMAS functionality to command and control message archiving ensures that all dispatcher actions, whether conveyed verbally or through digital signaling, are stored, validated, and retrievable with the same level of integrity, security, and temporal precision. This convergence is essential for achieving full traceability within modern software-centric dispatching architectures and for meeting contemporary safety, interoperability, and regulatory requirements.

CCRMAS User Interface

Users interact with the CCRMAS via a web interface presented in Figure 11. A registered user can access the CCRMAS from any computer within the local area network. The CCRMAS web user interface is localized, and records with an invalid checksum are

clearly visually distinguished. Various playback controls are available, including play, pause, mute, volume adjustment, a progress bar, and the ability to change playback speed.

The system is designed to provide users with a range of privileges, depending on their access level. These privileges allow users to perform actions such as downloading the metadata associated with audio records, downloading the audio records themselves, or even deleting them, but only after they have been listened to and verified by an authorized user. Audio recordings can be downloaded individually or as a ZIP archive.

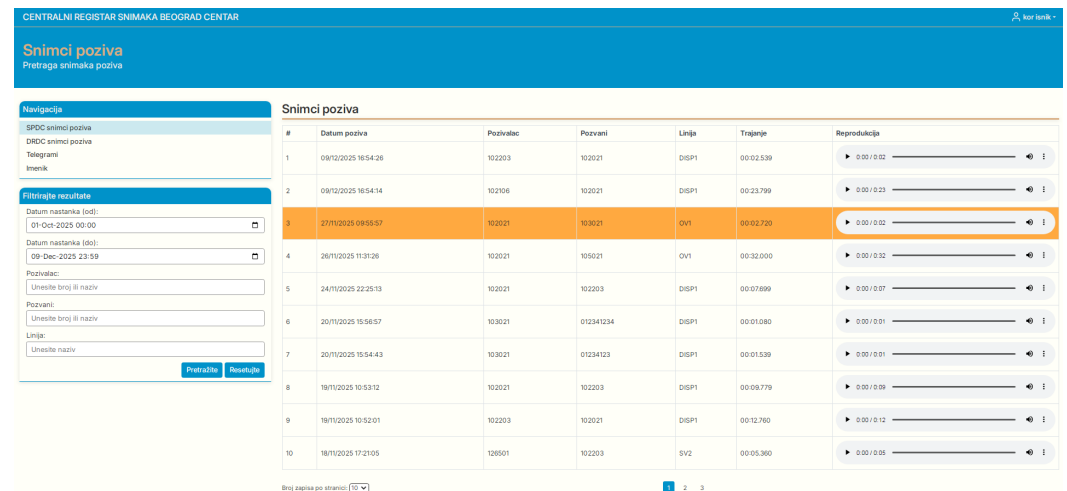


Figure 11. Web-based user interface of the CCRMAS, providing secure access to integrity-verified dispatcher voice and message records with role-based privileges, playback, auditing, and retrieval functionalities.

All actions related to the management of audio records, including deletions, metadata downloads, and audio records downloads, are logged for auditing purposes. This allows administrators to track changes, verify actions taken by users, and ensure compliance with internal policies or regulations regarding data management.

4.6. System Realization in an Operational Environment

The integrated digital dispatching system has been deployed along high-speed railway corridors, including the Belgrade–Novi Sad section. The RDCS, the DRDS, and the CCRMAS are independent functional modules that share the same IP-based transport layer and authentication framework, ensuring interoperability and unified supervision. Each dispatching center features redundant VoIP, supervisory and archival servers housed in standard 19-inch racks (Figure 12), with optical fiber backbone interconnection and distributed LAN infrastructure at station and regional levels.

Operational testing indicated seamless synchronization between dispatchers and locomotive radios, consistent voice quality, and reliable call logging; the corresponding validation results and system-level indicators are analyzed and summarized in Section 5. In addition, operational testing indicated resilience against power interruptions, temporary link failures, and database server restarts.



Figure 12. On-site deployment of the digital dispatching system, showing rack-mounted central equipment and dispatcher TC desk, illustrating practical integration of software-centric services within an operational railway environment.

5. Evaluation and Discussion

This section evaluates the proposed dispatching architecture based on system-level observations obtained during deployment and operation in an active railway environment. The evaluation focuses on operational continuity during migration, preservation of dispatcher workflows, traceability of communication, communication performance, and resilience of the integrated digital infrastructure. These aspects are assessed against the criteria and data sources summarized in Table 1. A structured comparison with the legacy system is subsequently provided to contextualize the observed improvements.

Table 1. Evaluation criteria and data sources.

Dimension	Metric/Evidence	Data Source	Rationale
Reliability	Call success rate during operational use; absence of packet loss under normal load	RTCP logs	Support for mission-critical voice communication
Availability	Redundant communication paths; absence of service interruption during incremental migration	Deployment and operational records	Continuous dispatching operation during modernization
Traceability	HMAC-verified records; time-aligned voice and command logs	CCRMAS archival database	Post-event analysis, accountability, and regulatory compliance
Scalability	Modular VoIP servers; distributed archiving components	Architectural and deployment analysis	Support for network expansion and long-term evolution

5.1. Incremental Migration and Operational Continuity

Operational deployment confirms that incremental migration from analog to IP-based dispatching can be achieved without interrupting railway operations. Legacy trackside telephones, radio base stations, and dispatcher workflows remained fully functional throughout the transition, while digital subsystems were progressively introduced at coordination and operational layers. This evaluation corresponds to the functional equivalence and availability criteria defined in Table 1.

The coexistence of analog field equipment with a software-enabled core demonstrates that staged modernization is a viable strategy for legacy-heavy railway networks. By preserving external interfaces and operational semantics while migrating internal system logic,

the approach significantly reduces deployment risk and avoids large-scale organizational disruption or retraining.

5.2. Interface-Level Adaptation and Functional Preservation

Interface-level adaptation proved sufficient to preserve established operational behavior across both fixed-line and radio-dispatching domains. Dispatchers continued to use familiar procedures, signaling tones, and call-handling semantics, while protocol adaptation, media conversion, and call control were handled transparently within the digital core.

This confirms that modernization at the system level does not require redesign of field equipment or their interfaces, provided that legacy signaling and procedural semantics are correctly encapsulated. The approach enables the introduction of centralized supervision, redundancy, and scalability while maintaining full functional continuity, which is essential in critical operational environments.

5.3. Unified Archiving, Traceability, and Voice Transmission Quality

The integration of the call records and messages archiving subsystems enables centralized, integrity-verified archiving of dispatcher voice communication and structured command and notification messages across both RDCS and DRDS subsystems. Compared to analog registrophone solutions, the system provides consistent time alignment across wired and radio domains, cryptographic verification of record origin and integrity, and rapid retrieval and correlation of voice records with operational actions. These results address the traceability and reliability dimensions defined in Table 1, supported by CCRMAS database records in Section 5.4 and RTCP-derived metrics in Table 2.

To assess the suitability of the IP-based voice communication subsystem under real operational conditions, quality-related parameters were collected during live dispatching communication using the RTP and the associated RTCP. This non-intrusive monitoring approach allows continuous observation of transmission characteristics without affecting normal system operation.

RTCP provides periodic sender and receiver reports containing standardized network and stream quality indicators, as defined in [35]. These reports were generated by the VoIP subsystem during regular dispatcher–operator voice sessions and logged by the communication server. The collected data therefore reflect actual network conditions, codec behavior, and end-to-end transmission performance encountered during field operation. The reports were produced at regular intervals of approximately a few seconds, enabling continuous observation of voice transmission parameters over the duration of each operational call.

The monitored parameters include round-trip time (RTT), packet loss statistics, inter-arrival jitter, and an internal quality indicator reported by the VoIP stack. Observed RTT values remained consistently low, indicating negligible end-to-end latency. No packet loss was observed in the analyzed sessions, while inter-arrival jitter remained bounded and stable throughout the calls, suggesting the absence of congestion or buffer instability. The reported quality indicator exhibited minimal variation over time, further confirming stable transmission conditions.

Table 2 summarizes the key RTP/RTCP-based metrics extracted from multiple live communication sessions. Although these parameters do not directly measure speech intelligibility, they are widely accepted as objective indicators of voice service suitability for real-time and mission-critical communication systems. To provide explicit standards-based validation, the observed delay, jitter, and packet loss values were evaluated against the European Telecommunications Standards Institute (ETSI) Telecommunications and Internet Protocol Harmonization Over Networks (TIPHON) Quality of Service (QoS) classification framework [36], which remains commonly referenced for quality categorization in VoIP

systems, with impairment metrics and thresholds consistent with the International Telecommunication Union—Telecommunication Standardization Sector (ITU-T), including [37] and [38]. In addition to the standardized RTP performance indicators, the Asterisk MES score was recorded as a proprietary composite quality indicator on a 0–100 scale derived from real-time media statistics within the VoIP subsystem. While MES does not correspond to an external normative standard, it provides an additional internal consistency metric reflecting media stability.

As shown in Table 2, all standardized QoS parameters remain within the ETSI TIPPHON reference thresholds (“Best” for delay and “Good” limits for packet loss and jitter). Because RTT represents a round-trip measurement, the corresponding end-to-end delay is approximately half of the observed RTT under symmetric network conditions and therefore remains well below the referenced limits. MES values consistently indicate stable media performance throughout the observation period.

The observed results therefore demonstrate that the proposed architecture not only ensures operational reliability but also satisfies externally defined QoS performance limits applicable to high-availability real-time communication systems.

Table 2. Summary of RTP/RTCP-based voice transmission metrics collected during field operation.

Parameter	Min	Max	Mean	Reference Threshold
RTT [ms]	3.4	17.3	~7	<300 ms (equivalent of end-to-end <150 ms ETSI TIPPHON “Best”)
Packet loss [%]	0	0	0	≤3% (ETSI TIPPHON “Good”)
RTP jitter [ms]	0	27	<10	≤75 ms (ETSI TIPPHON “Good”)
MES	87.9	88.1	88.0	Asterisk’s proprietary scale (0–100)

5.4. Resilience, Supervision, and Maintainability

The unified IP-based backbone enables redundancy and fault-tolerance mechanisms that were not available in earlier analog dispatching systems. Dual optical paths, redundant servers, distributed VoIP services, and replicated storage components allow localized failures to be isolated without global service disruption.

The client-side VoIP server selection mechanism was validated during regular operation by maintaining continuous dispatcher communication, with TC desks and VoIP endpoints transparently selecting available servers from the configured pool without requiring any changes to dispatcher workflows or operating procedures.

From a maintainability perspective, the migration of control, supervision, and recording functions into software-based services simplifies system evolution. Configuration changes, functional extensions, and diagnostics can be performed without physical rewiring or hardware replacement, supporting long-term adaptability under evolving operational and regulatory requirements.

Because all VoIP servers are functionally equivalent and selected dynamically by endpoints, system capacity can be expanded incrementally by adding servers to the pool without modifying dispatcher-facing interfaces or endpoint configuration logic.

To substantiate these architectural properties under real operational conditions, Table 3 summarizes the system-level indicators observed on an isolated track section during the period February 2025–January 2026 (a 354-day evaluation interval) under live system operation. In accordance with standard railway practice, ground–train communication on this section is event-driven and initiated only in specific operational situations requiring

coordination (e.g., movement authority updates or fault-related messages), rather than as part of continuous routine exchange.

Table 3. System-level operational indicators observed during field deployment.

Indicator	Observed Evidence	Interpretation
Operational continuity	No service interruption during incremental migration No dispatcher intervention required	Confirms availability and functional equivalence under live conditions
Voice communication reliability	2065 dispatcher voice calls recorded No detected archival data loss	Supports reliable mission-critical voice communication and recording
Traceability and auditability	2806 structured operational messages archived 70 message events correlated with subsequent voice calls	Enables cross-domain event reconstruction and post-incident analysis beyond legacy systems

The following subsections present operational data and statistical indicators extracted from the system, providing quantitative evidence aligned with the reliability, availability, and scalability criteria defined in Table 1. Although these indicators do not constitute formal Reliability, Availability, Maintainability, and Safety (RAMS) certification, they offer empirical support for improved reliability, maintainability, and safety oversight compared to legacy analog solutions.

5.4.1. Voice Call Activity and Duration Statistics

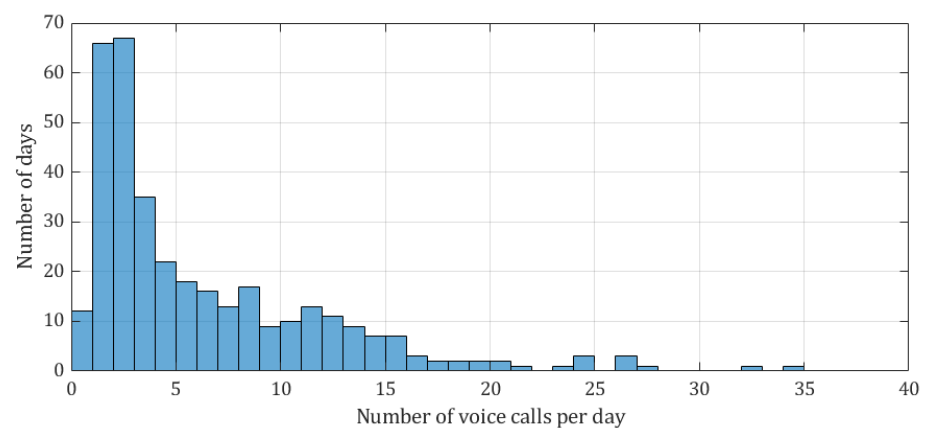
To complement the aggregate dispatcher voice call count in Table 3, the distribution of voice calls was analyzed to assess operational variability and load behavior over the observation period. Rather than relying solely on totals, the following statistics analyze the daily number of dispatcher calls and call recording duration, providing insight into operational workload, stability, and communication demand during live dispatching operations, as summarized in Table 4.

The observed daily call counts exhibit pronounced over-dispersion (variance significantly exceeding the mean), indicating that the traffic is more accurately characterized by a negative binomial distribution rather than a Poisson process [39]; this behavior is consistent with the system's state-dependent operational nature, where call intensity varies with operating conditions, and although such variability is expected, a detailed statistical analysis is beyond the scope of this paper.

Days with zero recorded dispatcher calls do not indicate system inactivity or communication failure; instead, they reflect the absence of operational situations requiring coordinated intervention, such as incident handling or fault-related notifications on the observed track section. As illustrated in Figure 13, the daily dispatcher call frequency exhibits variability characteristic of event-driven operational communication, including low-activity days and occasional higher-load periods. Importantly, no sustained high-load intervals or abrupt regime shifts were observed that would suggest operational stress or infrastructure instability. The overall pattern is consistent with routine dispatching activity driven by operational demand rather than continuous traffic exchange.

Table 4. Dispatcher voice call statistics (February 2025–January 2026; 354 days).

Statistic	Value
Total number of calls	2065
Number of invalid calls	36
Number of automatically terminated calls	11
Mean number of calls per day	5.8
Calls per day standard deviation	5.9
Median number of calls per day	3
Maximum number of calls per day	34
Minimum number of calls per day	0
Number of zero calls days	12

**Figure 13.** Histogram of daily dispatcher voice call counts (February 2025–January 2026).

Integrity verification results further support system robustness: more than 98% of recorded voice calls passed HMAC-SHA256 validation, while invalid recordings were retained but flagged as integrity-unverified and clearly distinguished visually in the user interface (Figure 11).

Table 5 summarizes the descriptive statistics of dispatcher voice call durations during the operational period. The resulting distribution indicates stable temporal characteristics of dispatcher communication, with limited variability and no extreme values suggestive of network congestion or service degradation.

The only notable anomaly is a cluster of voice calls with durations of 30 min, likely reflecting automatic call termination after a predefined system timeout threshold. These long-duration calls did not degrade system performance, as the architecture was designed to operate reliably under maximal expected load conditions, with sufficient processing and network capacity to sustain peak operational demand. Furthermore, the maximum allowable call duration is a configurable system parameter, enabling adaptation to specific operational or regulatory requirements. For clarity, calls terminated at the predefined timeout (30 min) were excluded from the statistics. Very short calls (minimum duration 0.1 s) correspond to immediately terminated or aborted sessions and do not represent completed conversational exchanges.

No additional anomalous duration patterns were observed, indicating consistent voice transmission and call handling under real operational conditions. The 95th percentile confirms that extended conversations constitute a limited share of total communication activity. The distribution remains right-skewed, reflecting predominantly short operational exchanges with a smaller proportion of longer coordination events.

Table 5. Dispatcher voice call duration statistics (February 2025–January 2026; 354 days) *.

Statistic	Value [s]
Mean call duration	31.2
Call duration standard deviation	47.8
Median call duration	15.8
Minimum call duration	0.1
Maximum call duration	268.9
95th percentile	148.3

* Automatically terminated calls (30 min) were excluded.

5.4.2. Structured Command/Notification Messages Distribution

In addition to voice communication, structured operational messages (telegrams) were analyzed to assess command activity patterns and archival completeness. Table 6 summarizes the distribution and integrity characteristics of telegrams recorded during live system operation (Table 3).

Table 6. Structured operational message statistics (February 2025–January 2026; 354 days).

Statistic	Value
Total number of messages	2806
Number of unique command types	21
Most frequent command type (count)	1448
Maximum telegrams per day	61
Minimum telegrams per day	0
Mean telegrams per day	7.9
Telegrams per day standard deviation	8.1
Median telegrams per day	6
Checksum validation rate	100%

The distribution of telegrams reflects sustained operational usage rather than isolated events. The complete checksum validation rate (100%) confirms the ingestion reliability of the archival subsystem and supports the integrity guarantees introduced by the proposed architecture and the resilient process described in Section 4.4. To evaluate temporal variability, the daily distribution of structured operational messages is presented in Figure 14.

The observed pattern exhibits variability characteristic of event-driven operational communication, including low-activity days and occasional higher-volume intervals. Importantly, no prolonged high-load periods or irregular inactivity gaps indicative of system malfunction were identified. The observed fluctuations therefore correspond to normal operational variation rather than infrastructural limitations.

5.4.3. Correlated Telegram-Call Latency Distribution

A subset of 70 telegram events correlated with subsequent voice call events (Table 3) was analyzed to quantify the interval between the telegram that initiated the interaction and the start of the associated voice call. The latency distribution, summarized in Table 7, provides a quantitative characterization of cross-domain temporal alignment and dispatcher response dynamics under live operational conditions.

The latency statistics reflect predictable timing intervals between telegram transmission and the subsequent beginning of voice communication. The observed latency range indicates bounded operational response intervals under real operating conditions. As shown in Figure 15, correlated events occur within a finite and consistent temporal window,

without prolonged delays or secondary clustering that would suggest systemic bottlenecks or queuing effects. In particular, 95% of correlated events occurred within 85.2 s of message creation. This behavior supports the suitability of the proposed architecture for time-sensitive dispatcher communication scenarios.

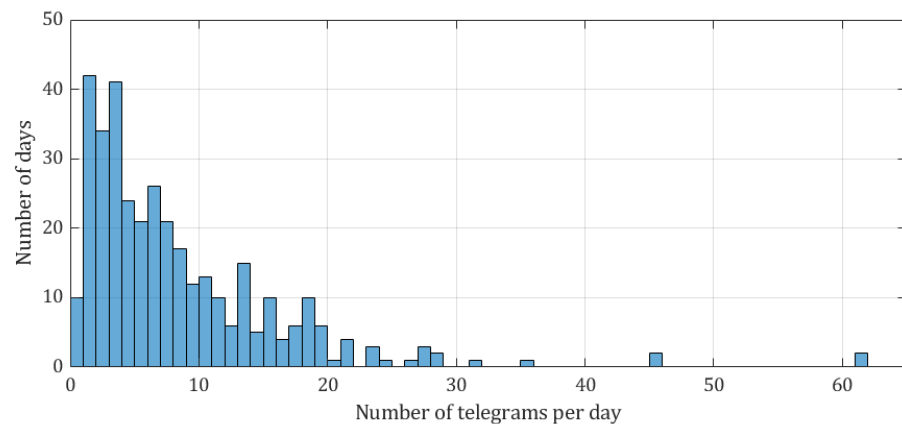


Figure 14. Histogram of daily structured operational message counts (February 2025–January 2026).

Table 7. Latency statistics for correlated message–voice call events (70 events).

Statistic	Latency (s)
Mean latency	23.6
Latency standard deviation	22.4
Median latency	16.8
Minimum latency	0.4
Maximum latency	106.8
95th percentile	85.2

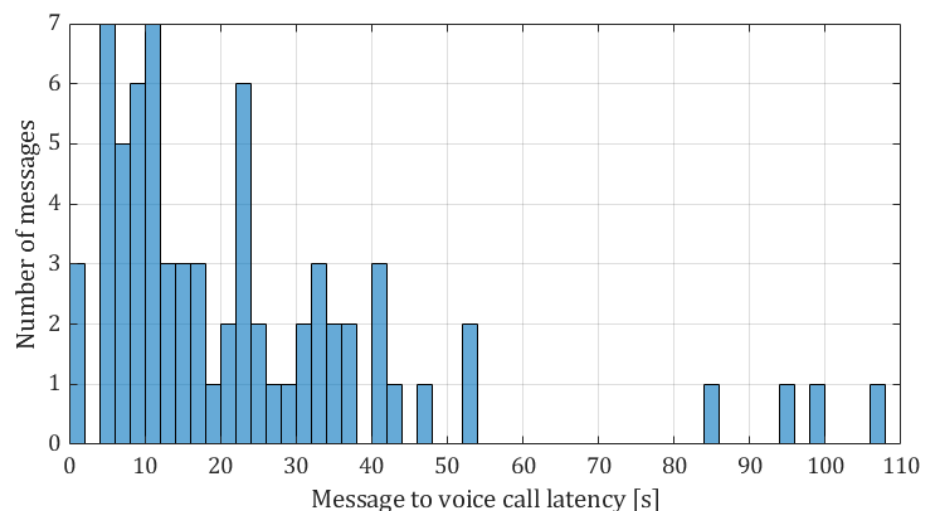


Figure 15. Distribution of latency between structured message initiation and corresponding dispatcher voice call start (70 correlated events).

5.5. Operational Improvements Relative to Baseline Legacy System

Direct quantitative comparison of the legacy dispatching system and the proposed software-centric dispatcher communication platform is inherently constrained, as the legacy architecture does not provide features demonstrated in the new communication system, such as centralized indexing, cryptographic integrity verification, or cross-domain correlation between voice records and operational command/notification messages. Consequently,

properties evaluated in Section 5.4 represent functional extensions rather than incremental performance improvements. For instance, while the legacy system offered no mechanism for correlating dispatcher voice communication with structured operational messages, the proposed platform enabled 70 verified voice–message correlation events during the observed operational period. Similarly, whereas the legacy system lacked cryptographic integrity and origin guarantees, more than 98% of recorded voice calls and all archived operational messages in the proposed system passed HMAC-SHA256 hash validation and invalid ones were automatically classified as integrity-unverified. These differences illustrate both the architectural discontinuity and the measurable operational impact of the modernization approach.

Table 8 summarizes the most prominent differences between the old system and the proposed communication platform, highlighting architectural and operational improvements relevant to recording, traceability, time alignment, cross-domain correlation, and migration risk.

Table 8. Legacy dispatching vs. proposed software-centric platform comparison.

Aspect	Legacy Systems	Proposed Platform
Recording	Voice-only, local hardware registraphone; manual record retrieval	Distributed recording and centralized archiving with filtering capabilities
Integrity	No integrity and cryptographic origin guarantees	HMAC-SHA256 verification and audit logging
Time alignment	Limited to local timestamps	NTP-based consistent timestamps across subsystems
Cross-domain correlation	Not possible: voice records and command/notification messages are in different domains	Unified storage enabling voice to message correlation
Migration risk	Replacement disruptive	Incremental coexistence via interface-level adaptation

The migration was completed without any increase in dispatcher-reported communication errors or delays, indicating that the new IP-based system (Table 2) meets or exceeds the operational performance of the analog system it replaced, while introducing enhanced functionality. Unlike the legacy recording systems, which lacked mechanisms for integrity verification, the CCRMAS achieves a 98% HMAC-SHA256 validation rate, providing, for the first time, cryptographically verifiable evidence suitable for post-event analysis.

5.6. Generalization and Limitations

To clearly position the proposed approach within the context of established architectural frameworks, Table 9 presents a structured comparison of representative railway communication and dispatching architecture families and the proposed hybrid migration model. This comparison is not intended to frame the proposed architecture as a substitute for GSM-R/FRMCS evolution; rather, it delineates the complementary problem space addressed herein, i.e., sustained hybrid coexistence, interface-level adaptation, and integrity-assured cross-domain recording within transitional operational constraints.

Table 9. Comparative analysis across architectural scope and migration strategy.

Dimension	Representative Existing Architecture Families		Proposed Hybrid Migration Architecture
	Radio Modernization (GSM-R/FRMCS)	IP-Native VoIP	
Primary scope	Evolution of railway mobile radio communications and interoperability.	End-to-end IP telephony for dispatching and group communications.	Hybrid integration and phased migration across analog fixed-lines, legacy tone-based radio signaling, and IP backbones.
Migration assumption	Progressive replacement/upgrade of the radio bearer and interfaces; coexistence may occur during rollout.	Assumes IP-capable endpoints and networks; legacy integration typically requires gateways.	Sustained coexistence of legacy and IP subsystems treated as a first-class architectural constraint.
Analog fixed-line dispatching	Not a primary concern of radio modernization programs.	Generally not inherent; may be supported via analog gateways.	Explicitly supported and preserved via interface-level adaptation.
Legacy tone-based radio signaling	Typically replaced or abstracted by digital radio services.	Generally not inherent; may be supported via specialized gateways.	Preserved and integrated as part of hybrid coexistence and migration.
Interface preservation at legacy boundary	Not central (focus is on radio services/interfaces).	Not central (focus is IP-native service delivery).	Explicit architectural principle (interface-level adaptation to preserve operational semantics).
Hybrid coexistence period	Common during rollout but often treated as transitional.	Usually minimized (prefer IP-only end-to-end).	Modeled as sustained operational reality under modernization constraints.
Contribution emphasis	Interoperable next-generation railway radio communications.	IP-based dispatching communications efficiency.	Hybrid migration strategy, interface preservation, and integrity-assured cross-domain evidence during modernization.

The presented approach does not replace future mobile-centric communication systems such as FRMCS. Instead, it complements them by providing a stable and auditable dispatching and archiving foundation during extended migration periods. Quantitative performance benchmarking beyond system-level indicators and large-scale comparative studies remain topics for future work.

Although the evaluation is grounded in the Serbian railway context, the observed results support broader applicability under similar constraints. Railway networks characterized by long asset life-cycles, mixed analog–digital infrastructure, and strict traceability requirements can benefit from the proposed methodology and architectural principles.

The operational evaluation presented in Sections 5.1–5.4 directly informed the design principles summarized in Section 6. In particular, the principle of interface-level adaptation was validated through uninterrupted migration and preservation of dispatcher workflows during live operation (Sections 5.1 and 5.2), while the principle of unified and integrity-verified archiving was supported by the observed traceability and time-aligned correlation of voice and command records across fixed-line and radio domains (Section 5.3). Furthermore, redundancy and modular software deployment principles were confirmed by the system’s fault-tolerance and maintainability characteristics observed during operational rollout (Section 5.4). This linkage demonstrates how system-level evaluation under real operational constraints leads to transferable architectural guidance beyond the specific case study.

6. Reproducibility and Deployment Transferability

While railway dispatching systems operate within sensitive and critical environments, scientific rigor requires that architectural decisions, protocol selections, and deployment constraints be described with sufficient precision to enable independent replication. In operational railway contexts, reproducibility cannot rely on disclosure of raw communication records or site-specific configurations; instead, it is achieved through explicit specification of architectural layers, standardized protocol interfaces, integrity safeguards, synchronization models, and system-level validation metrics. In response to RQ4, scientific contributions of this work were abstracted from the Serbia-specific case study and formalized as a generalizable hybrid migration architecture model, transferable design principles and deployment-level artifacts for legacy dispatching system modernization. They define the minimal technical and procedural conditions required to replicate the validated system behavior in other legacy-heavy railway networks, thereby enabling modernization under comparable operational constraints without exposing sensitive data.

6.1. Generalizable Hybrid Migration Architecture Model

Based on the architectural design and operational validation presented in Sections 4 and 5, the proposed dispatching solution was abstracted into a generalizable hybrid migration architecture model. This model formalizes incremental modernization of legacy-heavy railway dispatching environments by decomposing the system into four logically separated yet interoperable layers. The layering isolates legacy dependencies, enables controlled coexistence, and supports gradual evolution without operational disruption. These four layers define a reusable architectural pattern for the modernization of railway dispatching systems characterized by long asset life-cycles and regulatory traceability requirements.

The model explicitly treats incremental migration and legacy coexistence as first-class architectural constraints rather than transitional artifacts. Because each layer has clearly defined responsibilities and interfaces, the model can be replicated in other railway environments irrespective of specific radio technologies (e.g., GSM-R, FRMCS) or national deployment contexts.

Layer 1—Legacy Interface Layer.

The legacy interface layer comprises existing analog or long-lived field endpoints, including trackside telephones, radio base stations, locomotive radios, and established dispatcher operational workflows. This layer preserves historical signaling semantics, electrical characteristics, and procedural conventions. Crucially, no modifications to field equipment or dispatcher behavior are required at this layer. The preservation of external interfaces ensures functional continuity and minimizes migration risk in critical railway environments.

Layer 2—Adaptation Layer.

The adaptation layer provides controlled translation between legacy interfaces and modern digital infrastructure. It consists of media converters, protocol gateways, tone decoders, and analog-IP boundary components. This layer encapsulates legacy signaling and audio characteristics while exposing normalized digital interfaces to higher architectural layers. Interface-level adaptation enables prolonged coexistence of analog and IP-based systems and supports staged deployment across geographically distributed railway sections.

Layer 3—Software-Centric IP Core.

The software-centric core implements communication control, session management, supervision, and system orchestration within a unified IP-based environment. Dispatcher consoles, VoIP servers, call-control logic, and supervisory services operate within this

layer. By decoupling communication handling from dedicated hardware and relocating it into software-defined services, this layer enables scalability, redundancy, centralized supervision, and simplified configuration management. The IP core remains agnostic to the specific characteristics of the underlying legacy endpoints, which are fully encapsulated by the adaptation layer.

Layer 4—Integrity-Protected Archival Layer.

The integrity-protected archival layer provides unified acquisition, verification, indexing, and long-term storage of dispatcher voice communication and structured operational messages. Cryptographic integrity mechanisms (e.g., HMAC-based origin verification), transactional persistence models, time synchronization, and role-based governance controls ensure evidentiary robustness. This layer is logically independent from communication handling, enabling centralized traceability across heterogeneous fixed-line and radio domains.

6.2. Design Principles for Legacy Dispatching System Modernization

Based on the system-level evaluation presented in Section 5, the empirically confirmed architectural and methodological principles were generalized to abstract system-specific implementation details and enable transferability to other legacy-heavy railway dispatching environments. Each principle is mapped to the four-layer hybrid migration architecture model defined in Section 6.1 to make the architectural responsibility of the principle explicit.

1. Interface Preservation over Component Replacement:

Legacy operational behavior can be preserved by encapsulating existing analog and procedural interfaces instead of redesigning field equipment or dispatcher terminals. This principle is applicable when legacy field devices and dispatcher interfaces must remain operational due to regulatory, organizational, or training constraints; the associated trade-off is that it limits the degree of interface modernization and constrains the introduction of fundamentally new interaction models. This principle was validated through uninterrupted operation and preservation of established dispatcher workflows during live system deployment, as observed in the incremental migration and interface-level adaptation results presented in Sections 5.1 and 5.2, respectively. In terms of Section 6.1, this principle primarily constrains Layer 1 (Legacy Interface Layer) to remain unchanged and is realized through Layer 2 (Adaptation Layer), which encapsulates legacy semantics and exposes normalized digital interfaces to Layer 3 (Software-Centric IP Core).

2. Centralized, Integrity-Protected Archiving:

Unified and integrity-verified archiving of dispatcher voice communication and structured command and notification messages is essential for traceability, auditability, and post-event analysis in hybrid dispatching environments. This principle is applicable when regulatory compliance and communication accountability are required; the trade-off is increased complexity in storage management, security governance, and long-term data retention. The effectiveness of this principle was supported by evaluation results demonstrating time-aligned, integrity-verified archiving and correlation of voice and command records across fixed-line and radio domains, as discussed in Section 5.3. In terms of Section 6.1, this principle is implemented by Layer 4 (Integrity-Protected Archival Layer), fed by Layer 3 acquisition and supervision for voice sessions and, where applicable, by Layer 2 normalization of structured radio-domain messages prior to archival persistence and correlation.

3. System-Level Evaluation over Component Benchmarking:

In critical railway environments, validation based on operational continuity, functional equivalence, and system-level indicators is often more feasible and meaningful

than isolated component-level benchmarking. This approach is applicable where controlled experiments or intrusive testing are impractical, at the cost of reduced granularity in attributing performance characteristics to individual subsystems. The methodological rationale is reflected in the adopted evaluation approach, which relied on operational continuity, functional equivalence, and system-level performance indicators derived from live deployment, as outlined in Section 3.6 and demonstrated through the system-level validation results in Sections 5.1–5.4. In terms of Section 6.1, this principle implies end-to-end validation across Layers 1–4 (continuity at Layer 1, correctness of Layer 2 adaptation, service behavior and QoS at Layer 3, and evidentiary completeness/integrity and correlation at Layer 4).

4. Incremental Migration as a First-Class Architectural Requirement:

In railway dispatching systems characterized by long asset life-cycles and continuous operation, migration strategy should be treated as a core architectural constraint rather than a deployment afterthought. Explicit support for the prolonged coexistence of legacy and digital components enables staged modernization without service disruption, at the cost of increased architectural complexity during transition periods. The necessity and feasibility of treating migration as an architectural requirement were validated by the observed coexistence of analog and digital subsystems without service disruption, as reported in the operational continuity and resilience evaluation in Sections 5.1 and 5.4, respectively. In terms of Section 6.1, this principle is realized by keeping Layer 1 stable, using Layer 2 as the controlled coexistence boundary, migrating control and supervision into Layer 3, and enabling early consolidation of traceability and governance in Layer 4 without requiring disruptive field changes.

Together, these principles form a transferable methodological framework for the gradual modernization of legacy dispatching systems in railway networks characterized by long asset life-cycles, heterogeneous technology environments, strict operational requirements, and extended transition timelines.

6.3. Deployment-Level Reproducibility Artifacts and Protocols

Reproducibility is demonstrated through the following deployment-level artifacts, which define the minimal conditions required to replicate the validated system behavior (Section 5). These artifacts can be interpreted as reproducibility constraints associated with specific layers and with the interfaces between layers in Section 6.1 model, with particular emphasis on the adaptation interface between Layer 2 and Layer 3 and the archival interface between Layer 3 and Layer 4.

1. Protocol Stack Transparency

The architecture relies on standardized, openly documented protocols and standards:

- SIP (RFC 3261) for signaling;
- RTP/RTCP (RFC 3550) for real-time media transport and quality monitoring;
- SFTP for secure file transfer;
- NTP for distributed time synchronization;
- TCP/IP for internal DRDS processing and archival transport of normalized radio telegram data;
- In the radio domain, structured messages originate as UIC tone-based signaling over the analog dispatch channel and are normalized at the gateway boundary.

The use of open protocols ensures replicable signaling, media handling, and archival workflows without reliance on proprietary transport mechanisms. In terms of Section 6.1, this artifact specifies Layer 3 control/media behavior (SIP, RTP/RTCP), the Layer 3 to Layer 4 archival transfer interface (SFTP/TCP/IP), the cross-layer time

base needed for Layer 4 indexing (NTP), and the Layer 2 gateway boundary for radio message normalization.

2. Recording and Archival Format Specification

All dispatcher voice communications are recorded in a standardized WAV format (8 kHz, 16-bit PCM), accompanied by HMAC-SHA256 integrity verification metadata. Archival persistence follows an ACID-compliant consistency model with transactional transfer logic. These mechanisms ensure that recording authenticity, atomicity, and durability can be reproduced independently of specific server vendors. In terms of Section 6.1, this artifact constrains the recording outputs produced in Layer 3 (standardized WAV plus metadata) and the persistence guarantees enforced in Layer 4 (transactional, ACID-compliant archival storage).

3. Integrity and Authentication Mechanisms

Each recording artifact is cryptographically signed at acquisition using a symmetric HMAC key provisioned per VoIP server. Verification is performed prior to archival persistence. This integrity model, combined with audit-logged user actions, defines a reproducible evidentiary workflow suitable for regulatory environments. In terms of Section 6.1, integrity is a pipeline across Layers 3 and 4: Layer 3 performs signing at acquisition, and Layer 4 verifies integrity and governs evidentiary persistence and auditing.

4. Time Synchronization Model

All subsystems operate under a hierarchical NTP-based timing architecture with Stratum-1 local synchronization servers. Time-aligned indexing enables cross-domain correlation between voice calls and structured command/notification messages. Reproducibility therefore requires consistent distributed time management as a foundational architectural constraint. In terms of Section 6.1, this artifact is a cross-layer invariant required for Layer 3 timestamping and for Layer 4 time-aligned indexing and cross-domain correlation (including Layer 2-normalized message timelines).

5. Server Pool and Failover Logic

VoIP servers operate as functionally equivalent nodes within a client-side selection pool. No master-standby hierarchy is required. Endpoints maintain an ordered server list and automatically reconnect upon failure detection. This deployment pattern can be replicated using any SIP-compliant infrastructure supporting distributed session management. In terms of Section 6.1, this artifact specifies the resilience and redundancy behavior of Layer 3 (Software-Centric IP Core) while preserving Layer 1 operational continuity from the endpoint/workflow perspective.

6. Observable Validation Metrics Reproducibility is validated through system-level indicators rather than internal implementation inspection. These include:

- Call success rate and absence of packet loss,
- RTP/RTCP-derived latency and jitter metrics;
- Recording completeness and checksum validation rate;
- Voice-message temporal correlation statistics;
- Absence of service interruption during incremental migration.

In terms of Section 6.1, these indicators jointly validate end-to-end behavior across Layers 1–4 (service continuity at Layer 1, correctness of Layer 2 adaptation, Layer 3 signaling/media/QoS and acquisition, and Layer 4 completeness, integrity verification, and correlation).

The parameters listed in Table 10 define the minimal protocol and configuration conditions required to reproduce the functional, archival, and integrity behavior evaluated in Section 5. Site-specific values are intentionally omitted as they do not affect architectural replicability. In terms of Section 6.1, the protocols and parameters in Table 9 primarily

define the normalization interface between Layer 2 and Layer 3 (legacy-to-IP adaptation and session/media handling) and the archival interface between Layer 3 and Layer 4 (integrity-protected transfer and persistence), while keeping Layer 1 interfaces unchanged.

Table 10. Core protocols and configuration parameters enabling reproducible deployment.

Layer/Function	Protocol/Mechanism	Configuration Parameters
Session signaling	SIP (RFC 3261)	SIP over UDP/TCP; dispatcher line identification via logical extension mapping; server pool configuration for client-side failover
Media transport	RTP/RTCP (RFC 3550)	8 kHz PCM audio (WAV); RTCP sender/receiver reports enabled; jitter and round-trip time monitoring active
Voice recording format	WAV (PCM)	8 kHz sampling rate; 16-bit mono; deterministic file naming scheme including timestamp and logical endpoint ID
Data origin guarantees	HMAC-SHA256	Per-server symmetric key; checksum generated at acquisition; verification prior to archival persistence
Secure archival transfer	SFTP	Configurable polling interval; minimum file age threshold before transfer; atomic file write and acknowledgment procedure
Time synchronization	NTP	Hierarchical synchronization; centralized Stratum-1/Stratum-2 reference; millisecond-level timestamp resolution
Structured message signaling	UIC tone-based selective radio signaling	Telegram signaling over analog radio dispatch channel; decoding and normalization at IP gateway boundary
Data persistence	ACID-compliant consistency model	Transactional transfer, processing and storing operations (see Sections 4.4.5 and 4.5); indexed timestamp fields; redundant storage (e.g., RAID/NAS)
Server redundancy model	Distributed VoIP server pool	No master-standby hierarchy; client-side server selection; automatic reconnection on failure detection

6.4. Reproducible Migration Scenarios

To operationalize the proposed design principles and deployment-level reproducibility artifacts, several migration scenarios were distilled from the implementation experience. These scenarios abstract recurring transition patterns and demonstrate their applicability to legacy-heavy railway dispatching environments. Each scenario is expressed as a reproducible instantiation of the four-layer architecture model in Section 6.1, i.e., preserving Layer 1, inserting/expanding Layer 2, relocating control into Layer 3, and consolidating traceability in Layer 4.

6.4.1. Migration from Legacy Trackside Dispatching to RDCS

Reproducible migration from a legacy trackside dispatching system to the RDCS is achieved by preserving external operational interfaces while relocating communication handling, supervision, and recording functions into a software-centric IP core. The migration process begins with the identification of all legacy fixed-line communication paths, registraphone recording triggers, and dispatcher workflows. Rather than modifying dispatcher consoles or trackside telephones, digital interception points are introduced at

aggregation nodes by deploying VoIP servers and analog–IP gateways that transparently terminate legacy circuits, in accordance with the interface-preservation principle articulated in Design Principle 1. In terms of Section 6.1, this corresponds to preserving Layer 1, introducing interception and translation via Layer 2 at aggregation nodes, relocating control and recording into Layer 3, and consolidating evidentiary storage and governance in Layer 4. In addition, VoIP telephones are introduced as SIP-compliant endpoints within the software-centric IP core, enabling standardized call handling and distributed recording without altering legacy-facing operational semantics. This endpoint integration maintains functional continuity at the legacy interface while supporting reproducible session management and archival capture under the same protocol and integrity constraints defined for the migrated system.

All dispatcher voice sessions are established through the VoIP servers, where distributed digital acquisition replaces the centralized hardware regisphone. Recordings are generated in a standardized format, enriched with contextual metadata, and cryptographically protected at the point of acquisition. Secure, transactional transfer to the centralized CCRMAS archive provides integrity assurance, atomic persistence, and redundant storage, thereby sustaining the evidentiary guarantees of the legacy regisphone. These mechanisms directly correspond to the traceability and integrity criteria summarized in Table 1 and are reflected in the observed recording completeness and auditability indicators reported in Table 3. In terms of Section 6.1, this corresponds to preserving Layer 1, introducing interception and translation via Layer 2 at aggregation nodes, relocating control/recording into Layer 3, and consolidating evidentiary storage and governance in Layer 4.

Easy reproducibility of this migration strategy is supported by explicit adoption of the employed protocols (SIP, RTP/RTCP, SFTP, NTP), recording formats (WAV format), integrity mechanisms, and archival workflows, enabling independent replication of functional behavior without access to site-specific configurations or sensitive operational data. Validation is performed through parallel operation of the legacy regisphone and CCRMAS, allowing comparison of recording counts, timing consistency, and archival reliability, as reflected in the fixed-line operational evidence presented in Tables 3 and 8. This approach exemplifies Design Principles 2 and 3.

6.4.2. Migration from Legacy Radio-Dispatching to DRDS

Migration from legacy radio-dispatching systems to the DRDS follows the same reproducibility principles as legacy trackside dispatching to RDCS, while addressing the additional complexity of radio-domain signaling and mobile endpoints. Legacy radio base stations and locomotive radios are preserved, and interface-level adaptation is introduced through media converters that bridge UIC tone-based signaling and analog audio with the IP-based dispatching core. Dispatcher interaction semantics, operational calling procedures, and radio operating modes remain unchanged, directly reflecting the interface-preservation strategy formalized in Design Principle 1. In terms of Section 6.1, this preserves Layer 1 radio endpoints and procedures, extends Layer 2 with radio-specific tone decoding/normalization at the gateway boundary, relies on Layer 3 for session handling and acquisition, and uses Layer 4 for unified, integrity-protected archiving and correlation.

Voice communication between dispatchers and train drivers is digitized by routing all audio streams through VoIP servers, where recording and quality monitoring are performed using the same standardized mechanisms as in the fixed-line domain. In parallel, structured command and notification messages are transmitted via UIC tone-based selective signaling over the analog railway radio dispatch channel and are decoded at the media gateway boundary before being normalized and transferred to CCRMAS using secure,

transactional workflows. Both voice and message artifacts are time-aligned using a unified NTP infrastructure and protected by cryptographic integrity checks, enabling unified archival and cross-domain correlation. The effectiveness of this approach is demonstrated by the correlated voice-message events and message volumes reported in Table 3, and by the comparative improvements over legacy radio recording summarized in Table 8.

Reproducibility is achieved by specifying the message formats, transfer procedures, integrity verification steps, and correlation logic used to associate radio voice exchanges with command and notification events. Rather than exposing raw radio traffic or operational identifiers, anonymized aggregate indicators, such as dispatcher call counts, structured message volumes, correlation frequencies, and RTP/RTCP-derived quality metrics (Tables 2, 4, 6 and 7) provide sufficient evidence for independent validation under live operational constraints. This approach, exemplified in Design Principle 2 through unified, integrity-verified archiving across communication domains and Design Principle 4 by treating incremental migration and prolonged coexistence of analog and digital radio systems as first-class architectural requirements, enables replication of the migration methodology and its observable system-level behavior in other railway environments without requiring access to proprietary radio infrastructure or operational data.

6.4.3. Registraphone-to-CCRMAS Migration

The replacement of a legacy registraphone should be performed as a functional migration rather than a device substitution, in line with Design Principles 1 and 4. The process begins with the identification of all operational voice channels and regulatory recording requirements, followed by the introduction of digital interception points at aggregation nodes without altering dispatcher consoles or field equipment. Voice acquisition is distributed to VoIP servers or media gateways, where all calls are automatically recorded in a uniform archival format and cryptographically signed at the source. Recordings are securely transferred to a centralized CCRMAS archive using transactional workflows that enforce integrity verification, atomic persistence, and redundant storage, corresponding to the traceability and integrity criteria summarized in Table 1 and the archival reliability evidence reported in Table 3. Data retention, backup strategies, and immutability of evidentiary records are governed through configurable retention policies, cryptographic integrity verification, and audit-logged lifecycle management, ensuring compliance with regulatory and operator investigative requirements. In terms of Section 6.1, this preserves Layer 1 recording semantics and dispatcher workflows, uses Layer 2 interception where needed, relocates acquisition into Layer 3, and establishes Layer 4 as the authoritative integrity-protected evidentiary archive with governance and retention controls.

Indexed data retrieval and audit logging replace manual playback, while dispatcher workflows and recording semantics remain unchanged, preserving functional equivalence with the legacy system as demonstrated by the comparison in Table 8. During transition, CCRMAS operates in parallel with the legacy registraphone to validate recording completeness, timing consistency, and regulatory compliance before legacy hardware is decommissioned, consistent with the system-level validation approach advocated in Design Principle 3. This approach preserves operational continuity while extending recording scope to include structured command and notification messages, enabling unified, time-aligned, and integrity-protected archival across different dispatching domains, as evidenced by the correlated voice and message records reported in Table 8.

6.4.4. Integration of GSM-R Successors and FRMCS-Compatible Radio Protocols

The introduction of next-generation railway mobile communication protocols, such as GSM-R successors and the FRMCS, can be accommodated within the proposed dispatching

communication architecture without redesign of dispatcher-facing systems or centralized archiving mechanisms. Rather than treating the radio protocol transition as a system replacement, new protocol integration is achieved through interface-level adaptation at the radio access boundary, preserving dispatcher workflows, call-handling semantics, and recording requirements in accordance with Design Principle 1. In terms of Section 6.1, technology evolution is localized to Layer 2 (protocol-specific gateways and normalization), while Layer 3 (software-centric dispatching core) and Layer 4 (integrity-protected archiving) remain stable and Layer 1 dispatcher-facing workflows remain unchanged.

In this migration scenario, FRMCS or GSM-R successor radio access networks replace or coexist with legacy radio subsystems at the transport and signaling layers, while dispatcher interaction remains mediated through the same DRDS logical services. Voice streams and operational signaling exchanged with mobile units are terminated at protocol-specific gateways and normalized into the IP-based software-enabled dispatching core, where communication handling, recording, and supervision are performed using the same SIP, RTP/RTCP, and secure archival workflows as described for legacy radio migration in Section 4.3. As a result, the CCRMAS remains agnostic to the underlying radio technology and continues to provide unified, integrity-protected archiving of dispatcher voice communication and structured command and notification messages.

Reproducibility of this integration approach is ensured by explicit specification of protocol adaptation points, normalization interfaces, and recording workflows rather than disclosure of radio-layer implementations or proprietary configurations. Observable system behavior, such as recording completeness, time alignment, message–voice correlation, and communication quality, is evaluated using the same system-level indicators and aggregate metrics applied in Section 5. In particular, the traceability, reliability, and scalability criteria summarized in Table 1, the architecture comparison presented in Table 8, and the operational evidence reported in Tables 2 and 3 remain applicable irrespective of the underlying radio protocol.

This approach exemplifies Design Principle 2 by maintaining a single authoritative evidentiary layer across heterogeneous radio technologies, and Design Principle 4 by explicitly supporting prolonged coexistence of legacy radio systems and GSM-R-based and/or FRMCS compatible deployments. By decoupling dispatching and archival functions from radio access technology evolution, the proposed architecture enables reproducible, low-risk adoption of future railway communication standards without compromising operational continuity or traceability guarantees.

7. Research Question Closure

Based on the system-level evaluation presented in Section 5 and formalization into transferable generalizable solutions in Section 6, the research questions defined in Section 1 are answered as follows.

- RQ1 is validated by the demonstrated preservation of dispatcher workflows and signaling semantics during incremental migration (Sections 5.1 and 5.2).
- RQ2 is validated by the completeness, integrity, and time-aligned correlation of voice and command records provided by the CCRMAS (Section 5.3).
- RQ3 is addressed by the use of operationally derived system-level indicators in lieu of intrusive testing (Sections 3.6 and 5 and Tables 2 and 3).
- RQ4 is answered by abstraction of these results into generalizable hybrid migration architecture model, transferable design principles, and deployment artifacts (Section 6).

8. Conclusions and Future Work

This paper examined the digital transformation of railway traffic dispatching systems from a system-design and research perspective, addressing the challenge of modernizing critical, legacy-heavy communication infrastructure without disrupting ongoing operations. Rather than pursuing replacement-driven modernization, the work focused on incremental migration, interface preservation, and software-centric integration under real operational constraints.

The presented approach demonstrated that a hybrid dispatching architecture, combining legacy analog endpoints with an IP-based, software-enabled core, can preserve established dispatcher workflows and signaling semantics while enabling modern capabilities such as centralized supervision, redundancy, and integrity-verified archiving. The integrated deployment of fixed-line dispatching, radio dispatching, and centralized archiving subsystems provides a unified communication environment across heterogeneous wired and radio domains, supporting operational continuity during extended transition periods.

From a methodological standpoint, the results confirm that interface-level adaptation is sufficient to encapsulate legacy operational behavior and signaling procedures, allowing modernization at the system level without redesigning field equipment or retraining personnel. This approach reduces deployment risk, supports phased investment, and is particularly well-suited to railway infrastructures characterized by long asset life-cycles and strict requirements.

A key outcome of the presented architecture is the unification of dispatcher voice communication with structured command and notification message archiving. By applying integrity verification, consistent time synchronization, and centralized indexing across relevant communication domains, the system enhances traceability, post-incident analysis, and regulatory compliance beyond what is achievable with traditional analog recording solutions.

The presented approach complements, rather than replaces, mobile-centric railway communication systems such as GSM-R successors and FRMCS. While next-generation mobile technologies address broadband and train-centric communication needs, the proposed dispatching architecture provides a stable and auditable foundation for dispatcher communication during prolonged periods of technological coexistence and migration. Accordingly, the contributions of this work should be interpreted as advances in dispatching communication infrastructure and archival supervision, rather than in centralized traffic control or signaling system design.

Although the evaluation was based primarily on qualitative system-level validation under operational conditions, the findings indicate that the proposed methodology and architectural principles are transferable to other railway networks facing similar modernization challenges. Future work will focus on extending the software-centric dispatching platform toward advanced analytics and decision-support functions, including speech-to-text transcription for automated log generation, correlation of communication records with signaling and traffic data, predictive monitoring of dispatcher communication patterns, and deeper integration with emerging railway interoperability frameworks.

To support reproducibility and transferability, the modernization approach is described through explicit architectural layers, interface-level constraints, system-level evaluation criteria (Section 3.6), and operational indicators (Section 5). By grounding the derived generalizable hybrid migration architecture model Section 6.1 and design principles (Section 6.2) in traceable evaluation results and clearly defined validation metrics, the study provides methodological guidance that can be systematically replicated in other legacy-heavy railway environments under comparable operational constraints. Furthermore, reproducibility artifacts (Section 6.3) and explicitly defined migration scenarios

(Section 6.4) are provided to concretely demonstrate how the proposed design principles can be operationalized in practice. These artifacts enhance methodological transparency and facilitate structured replication in other railway environments.

While the proposed architecture does not perform centralized traffic control or signaling functions, it was designed to operate in coexistence with ERTMS-based and other centralized traffic control systems. By focusing on dispatching communication and integrity-protected archiving, the system provides a stable and auditable communication layer that can support centralized traffic control environments through standardized interfaces and interface-level adaptation. In this sense, the presented solution represents a suitable foundation for future integration with centralized traffic control platforms, without constraining their internal control, decision-making, or safety mechanisms.

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