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MICROELECTRONIC AND MICROPROCESSOR-BASED AUTOMATIC BLOCK SIGNALING SYSTEMS: ARCHITECTURE, FUNCTIONAL ANALYSIS, AND DIGITALIZATION PROSPECTS

Zh. Mengxu*
Engineering and Technology College of Yangtze University, Jingzhou, China.
E-mail: zhangmengxu@163.com

Zhang Mengxu — researcher, Engineering and Technology College of Yangtze University, PRC, Jingzhou, China
E-mail: zhangmengxu@163.com, https://orcid.org/0000-0003-1876-4044.

Abstract. This article presents a comprehensive technical analysis of microelectronic and microprocessor-based automatic block signaling (ABS) systems applied in railway train separation control. Four generations of electronic ABS equipment — AB-ChKE, AB-E1, AB-E2, and AB-UE — are examined from the perspectives of architectural design, signal processing methodology, fault tolerance, and integration with modern intelligent infrastructure management systems. The study addresses functional principles of microprocessor track receivers, the Boosting-based adaptive threshold algorithm for shunt detection, dual-channel and triplicated majority-vote redundancy structures, and digital signal processing techniques including two-phase differential modulation and the modified Bauer code with code distance d=4. The architecture of the unified AB-UE system is analyzed in particular detail, as it represents the most advanced implementation of the electronic ABS series, featuring full hardware unification, embedded remote monitoring, networkable transceivers, and condition-based maintenance capability. A quantitative comparative analysis across all four systems is provided, covering carrier frequency allocation, ballast resistance operating range, receiver sensitivity, output power, network data rate, and reliability metrics. The integration of ABS systems with SCADA platforms, PLC controllers, and IoT-based monitoring is assessed, and the transition pathway toward Industry 4.0-compliant predictive maintenance is evaluated. The results demonstrate that the AB-UE system reduces false-clear events by 85 to 90 per cent compared with relay-based ABS, extends maintenance intervals from 3 to over 12 months, and enables real-time dispatch monitoring of train positions, signal aspects, rail circuit voltages, and equipment faults. The findings provide an engineering and methodological basis for ABS modernization programs on Kazakhstan and CIS railway networks within the framework of the Transport Strategy 2030.

Keywords: automatic block signaling, microprocessor railway automation, ALS-EN, tonal rail circuit, SCADA, predictive maintenance, Industry 4.0, digital signal processing, fault tolerance, train detection

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МИКРОЭЛЕКТРОНДЫ ЖӘНЕ МИКРОПРОЦЕССОРЛЫҚ АВТОМАТТЫ БЛОКТАУ ЖҮЙЕЛЕРІ: АРХИТЕКТУРАСЫ, ФУНКЦИОНАЛДЫҚ ТАЛДАУЫ ЖӘНЕ ЦИФРЛАНДЫРУ ПЕРСПЕКТИВАЛАРЫ

Чжан Мэнсю*

Янцзы университетінің Инженерлік-технологиялық колледжі, Цзинчжоу, Қытай.
E-mail: zhangmengxu@163.com

Чжан Мэнсю — зерттеуші, Янцзы университетінің Инженерлік-технологиялық колледжі, Цзинчжоу, Қытай.
E-mail: zhangmengxu@163.com, https://orcid.org/0000-0003-1876-4044.

Аннотация. Мақалада теміржол қозғалысын интервалдық реттеуде қолданылатын микроэлектронды және микропроцессорлық автоматты блоктау (АБ) жүйелеріне кешенді техникалық талдау жүргізілген. AB-ChKE, AB-E1, AB-E2 және AB-UE электрондық автоматты блоктау құрылғыларының төрт буыны архитектуралық құрылымы, сигналдарды өңдеу әдістері, ақауларға төзімділігі және интеллектуалды инфрақұрылымдық басқару жүйелерімен интеграциялануы тұрғысынан қарастырылған. Зерттеуде микропроцессорлық рельстік қабылдағыштардың жұмыс қағидалары, шунтты анықтаудың Boosting негізіндегі адаптивті шекті алгоритмі, екіарналы және үшарналы majority-vote резервтеу құрылымдары, сондай-ақ екіфазалы дифференциалды модуляция және кодтық арақашықтығы d=4 болатын модификацияланған Bauer коды сияқты цифрлық сигналдарды өңдеу технологиялары талданған. Бірыңғайланған AB-UE жүйесінің архитектурасына ерекше назар аударылған, себебі ол аппараттық унификацияны, қашықтықтан мониторингті, желілік трансиверлерді және техникалық қызмет көрсетуді күй бойынша ұйымдастыру мүмкіндігін біріктіретін электрондық автоматты блоктау жүйелерінің ең жетілдірілген үлгісі болып табылады. Барлық төрт жүйе бойынша тасымалдаушы жиіліктер, балласт кедергісінің жұмыс диапазоны, қабылдағыш сезімталдығы, шығыс қуаты, желілік деректер алмасу жылдамдығы және сенімділік көрсеткіштері қамтылған сандық салыстырмалы талдау ұсынылған. Сонымен қатар АБ жүйелерінің SCADA платформаларымен, PLC-контроллерлерімен және IoT-негізіндегі мониторинг жүйелерімен интеграциясы қарастырылып, Industry 4.0 талаптарына сәйкес предиктивті техникалық қызмет көрсетуге көшу перспективалары бағаланған. Зерттеу нәтижелері көрсеткендей, AB-UE жүйесі релелік автоматты блоктау жүйелерімен салыстырғанда жалған бос көрсетулер санын 85–90 %-ға азайтады, техникалық қызмет көрсету аралығын 3 айдан 12 айдан жоғары мерзімге дейін ұзартады және поезд қозғалысын, бағдаршам көрсеткіштерін, рельстік тізбек кернеулерін және жабдық ақауларын нақты уақыт режимінде диспетчерлік бақылауға мүмкіндік береді. Алынған нәтижелер Қазақстан және ТМД елдерінің теміржол желілерінде «Көлік стратегиясы – 2030» аясында автоматты блоктау жүйелерін жаңғырту бағдарламалары үшін инженерлік және әдістемелік негіз бола алады.

Түйін сөздер: автоматты блоктау, микропроцессорлық теміржол автоматикасы, ALS-EN, тональды рельстік тізбек, SCADA, предиктивті техникалық қызмет көрсету, Industry 4.0, цифрлық сигналдарды өңдеу, ақауларға төзімділік, поезд анықтау

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МИКРОЭЛЕКТРОННЫЕ И МИКРОПРОЦЕССОРНЫЕ СИСТЕМЫ АВТОМАТИЧЕСКОЙ БЛОКИРОВКИ: АРХИТЕКТУРА, ФУНКЦИОНАЛЬНЫЙ АНАЛИЗ И ПЕРСПЕКТИВЫ ЦИФРОВИЗАЦИИ

Чжан Мэнсю*
Инженерно-технологический колледж Университета Янцзы, Цзинчжоу, Китай.
E-mail: zhangmengxu@163.com

Чжан Мэнсю — исследователь, Инженерно-технологический колледж Университета Янцзы, Цзинчжоу, Китай
E-mail: zhangmengxu@163.com, https://orcid.org/0000-0003-1876-4044.

Аннотация. В статье представлен комплексный технический анализ микроэлектронных и микропроцессорных систем автоматической блокировки (АБ), применяемых в системах интервального регулирования движения поездов. Рассмотрены четыре поколения электронных устройств автоматической блокировки — AB-ChKE, AB-E1, AB-E2 и AB-UE — с позиций архитектурного построения, методов обработки сигналов, отказоустойчивости и интеграции с современными интеллектуальными системами управления инфраструктурой. В исследовании проанализированы принципы работы микропроцессорных рельсовых приемников, адаптивный пороговый алгоритм обнаружения шунта на основе метода Boosting, двухканальные и трехканальные структуры резервирования majority-vote, а также технологии цифровой обработки сигналов, включая двухфазную дифференциальную модуляцию и модифицированный код Бауэра с кодовым расстоянием d=4. Особое внимание уделено архитектуре унифицированной системы AB-UE, представляющей наиболее совершенную реализацию электронных систем автоматической блокировки благодаря полной аппаратной унификации, встроенному удаленному мониторингу, сетевым трансиверам и поддержке технического обслуживания по фактическому состоянию. Представлен количественный сравнительный анализ всех четырех систем, охватывающий диапазоны несущих частот, рабочие диапазоны сопротивления балласта, чувствительность приемников, выходную мощность, скорость сетевого обмена данными и показатели надежности. Рассмотрена интеграция систем АБ с платформами SCADA, PLC-контроллерами и IoT-системами мониторинга, а также оценены перспективы перехода к предиктивному техническому обслуживанию в рамках концепции Industry 4.0. Результаты исследования показывают, что система AB-UE снижает количество ложных свободностей на 85–90 % по сравнению с релейными системами автоматической блокировки, увеличивает интервалы технического обслуживания с 3 месяцев до более чем 12 месяцев и обеспечивает диспетчерский мониторинг поездного положения, показаний светофоров, напряжений рельсовых цепей и неисправностей оборудования в режиме реального времени. Полученные результаты могут служить инженерной и методологической основой для программ модернизации систем автоматической блокировки на железных дорогах Казахстана и стран СНГ в рамках реализации «Транспортной стратегии – 2030».

Ключевые слова: автоматическая блокировка, микропроцессорная железнодорожная автоматика, ALS-EN, тональная рельсовая цепь, SCADA, предиктивное техническое обслуживание, Industry 4.0, цифровая обработка сигналов, отказоустойчивость, обнаружение поездов

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Introduction.

The reliability and throughput capacity of railway networks are fundamentally governed by the performance of train separation systems. Automatic block signaling (ABS) constitutes the primary layer of these systems, providing continuous determination of track section occupancy and generating the signal aspects that regulate train movement intervals. Over the past four decades, the ABS domain has undergone a decisive transition from relay-based relay-contact technology to microelectronic and fully digital microprocessor-based architectures, a process closely parallel to the broader computerization of railway infrastructure (Bryleev et al., 1984: 12–28; Sultangazinov, 2004: 45–67).

The growing intensity of railway operations on Kazakhstan main lines, combined with requirements for integration with the European Train Control System (ETCS) Level 2, implementation of Industry 4.0 principles, and the objectives of the Kazakhstan Transport Strategy 2030, creates new demands for ABS accuracy, reliability, and remote diagnostics capability. Under these conditions, a systematic technical analysis of the four principal electronic ABS generations — AB-ChKE, AB-E1, AB-E2, and AB-UE — and their integration pathways with SCADA, IoT, and predictive maintenance platforms acquires both scientific and applied significance (Pereburov et al., 2018: 12–19; Sultangazinov et al., 2022: 18–27).

Previous works have addressed individual aspects of microprocessor ABS. Bryleev et al. (1984) and Pereburov et al. (1984) established the theoretical foundations of railway automation and telemechanics, including early digital circuit designs. Sultangazinov (2004, 2009) provided systematic treatment of ABS elements and station systems in the Kazakhstan context. Shishmarev (2004) analyzed typical elements of automatic control systems applicable to programmable logic implementations. However, a consolidated comparative analysis of all four electronic ABS generations, integrating signal processing theory, fault tolerance architecture, and modern SCADA/IoT integration, has not been presented in the reviewed literature.

The object of investigation is the equipment of electronic automatic block signaling systems of series AB-ChKE, AB-E1, AB-E2, and AB-UE as applied on single-track and double-track railway lines with autonomous and electric traction. The subject of investigation is the functional architecture, signal processing methods, fault tolerance structures, and digital infrastructure integration of these systems.

The aim of the research is to perform a systematic comparative analysis of the four electronic ABS generations, to quantify their technical performance parameters, and to assess the prospects for their integration with intelligent transport infrastructure management within the Industry 4.0 paradigm.

The research tasks are as follows:

– to analyze the functional architecture and signal processing principles of AB-ChKE, AB-E1, AB-E2, and AB-UE systems;

– to compare technical performance parameters across the four generations in a unified tabular format;

– to assess the fault tolerance and self-diagnostic capabilities of each system generation;

– to evaluate the integration capability of ABS systems with SCADA, PLC, and IoT monitoring platforms;

– to determine the prospects for predictive maintenance implementation based on remote diagnostic telemetry from AB-UE network systems.

The scientific novelty of the study consists in the first systematic four-way comparative characterization of the electronic ABS series (AB-ChKE through AB-UE), including a quantitative performance analysis incorporating SCADA integration capability and predictive maintenance feasibility. The practical significance lies in providing engineering foundations for ABS modernization decision-making on Kazakhstan and CIS railway networks.

Materials and methods.

The methodological basis of the study comprises: (1) structural-functional analysis of ABS equipment based on technical documentation, regulatory standards (GTSS, MPS instructions), and academic monographs; (2) comparative analysis of signal processing methods and fault tolerance structures across system generations; (3) quantitative parameter comparison using published equipment specifications; and (4) evaluation of SCADA and IoT integration pathways based on modern railway automation literature.

Primary source materials include the foundational monographs of Bryleev et al. (1984), Sultangazinov (2004, 2009, 2022), and Shishmarev (2004), supplemented by recent publications on intelligent railway systems (Pereburov et al., 2018; Egorova et al., 2020) and digitalization of transport automation (Liukai et al., 2022).

The study proceeded through four sequential stages: (1) decomposition of each ABS system into functional blocks (transmitter, receiver, interface, signal relay, diagnostic, and network modules); (2) identification of the signal processing algorithms employed (adaptive threshold, Bauer coding, DPDM modulation, majority voting); (3) tabular comparison of electrical parameters, coding methods, and reliability characteristics; and (4) assessment of SCADA/IoT integration architecture for the AB-UE network subsystem.

The research hypothesis holds that the progressive evolution from relay-contact to fully digital microprocessor-based ABS, culminating in the unified AB-UE system, delivers quantifiable improvements in false-indication rates, maintenance intervals, and dispatch monitoring capability that fulfill the requirements of railway network digitalization under Industry 4.0 principles.

Results and discussion.

In contemporary railway signaling and control (RSC) practice, increasing attention is being given to systems based on microelectronic elements. Programmable-logic microprocessor technology offers decisive advantages in this context: the ability to implement algorithms of any required complexity, to create universal hardware blocks adaptable to diverse operational conditions, and to modify algorithms or operating parameters without hardware replacement — by updating software alone (Sultangazinov, 2004: 89–97).

The broad capabilities of programmable logic enable the implementation of self-checking and structural reconfiguration upon fault detection, diagnostics of controlled objects, and a wide range of service functions. Microprocessor RSC systems provide straightforward interfacing with higher-level automated management systems (SCADA, CTC), and perform automated registration and documentation of faults, non-standard actions of operating personnel, and other significant events — thereby forming the foundational data layer for predictive maintenance analytics (Pereburov et al., 2018: 22–30).

Two principal directions of contactless ABS development are recognized: (1) electronic ABS of the KEB type; and (2) electronic systems of the unified series on a new component base. The latter direction encompasses the AB-ChKE, AB-E1, AB-E2, and AB-UE systems, which share common design principles but differ in their application domain, hardware implementation, and functional capability.

The AB-ChKE system represents the first significant step toward microprocessor-based ABS, achieved by replacing the relay-based path receiver of conventional numeric code ABS with a microprocessor track receiver (MPP-ChKE) while retaining relay-contact signal relay logic. The signal installation equipment of AB-ChKE comprises: the MPP-ChKE microprocessor path receiver; signal relays Zh (Yellow), ZhZ (Yellow-Green), Z (Green); and rail circuit matching and protection devices (USZ).

The MPP-ChKE path receiver is implemented as a dual-channel information processing structure. Both channels operate simultaneously, but only the outputs of the leading (master) channel are used for ABS operation. Each channel contains two central processor units and a monitoring circuit that continuously compares the states of control nodes between the two processors, implementing a hardware-level consistency check.

The central processors perform demodulation and decoding of received numeric code signals, and generate coded signals for transmission to the preceding signal installation. A key innovation is the adaptive threshold algorithm embedded in the receiver software, based on the method of change-point detection in stochastic processes (Sultangazinov, 2009: 67–75). This algorithm provides automatic adjustment of the train shunt detection threshold and the receiver return coefficient in response to changes in ballast resistance. Formally, the adaptive threshold U_{th} is updated at each sampling interval according to:

$$U_{th}(t) = U_{th}(t-1) + \alpha \cdot [\mu_{free}(t) - \mu_{shunt}(t-1)] \quad (1)$$

where α is the adaptation gain coefficient ($0 < \alpha \le 1$), μ_free(t) is the running mean of the receiver input signal under free-track conditions, and μ_shunt(t−1) is the running estimate of the signal under shunted conditions from the previous sampling window. This adaptation mechanism eliminates the false-clear risk that arises from short-term shunt loss under wet or contaminated ballast conditions.

The interface module of MPP-ChKE performs: channel switchover when the master channel fails; verification of transmitted code combinations; monitoring of signal lamp filament integrity; and interfacing with dispatch monitoring systems. It incorporates a contactless current commutator for code signal modulation and power amplifiers for signal relay actuation.

The AB-ChKE system provides four-aspect signaling by decoding all three numeric code signals (unlike conventional ABS which decodes only two). It was recommended under the Accelerated Technical and Technological Reequipment Programme for equipping Category 2 and Category 3 railway lines, and was designed to enable phased relay cabinet replacement as a modernization pathway for existing numeric code ABS.

The AB-E1 system introduces a fundamentally new rail circuit concept: continuous alternating current rail circuits operating at a carrier frequency of 174.38 Hz, selected to optimize interference immunity, code combination length, and rail line signal attenuation to achieve practical RC lengths up to 2500 m (Sultangazinov et al., 2022: 28–35).

The microprocessor path receiver of AB-E1 employs the same adaptive threshold and change-point detection algorithms as AB-ChKE, but the dual-set receiver structure (with identity verification between sets) provides significantly improved reliability under electromagnetic interference conditions. The RC free condition yields an input signal amplitude of approximately 3 V; occupation is declared when the signal falls below the 0.55 V actuation threshold.

Signal interlocking between adjacent block section semaphores in AB-E1 is accomplished by radio-type transmission along the rail line, using the binary 8-bit modified Bauer code with code distance $d = 4$, which supports 16 distinct messages and provides high protection against transmission distortions (Egorova et al., 2020: 45–52). The code distance $d = 4$ guarantees detection of any triple-bit error and correction of any double-bit error in transmitted code words.

Signal formation employs two-phase differential modulation (DPDM), which organizes two parallel phase subchannels within each message: an information subchannel (conveying track state data) and a synchronization subchannel (carrying the frame synchronization signal and block section identifier). For each track of a double-track section, two synchronization groups alternate in adjacent RCs, providing protection against isolating joint breakdown and against interference from parallel-track RCs.

The transceiver unit performs demodulation and decoding only when the guard block section RC is confirmed free, via the front contact of the path relay. When the RC is occupied, the transceiver disconnects from the rail line and enters continuous self-test mode, preventing fault accumulation. The transceiver is implemented as a triplicated majority-vote structure: when any two of three processing sets agree on output state, the majority decision is adopted and the non-conforming set is diagnosed and isolated:

$$Y = majority(y_1, y_2, y_3) = (y_1 \wedge y_2) \vee (y_1 \wedge y_3) \vee (y_2 \wedge y_3) \quad (2)$$

where y_1, y_2, y_3 are the binary output states of the three processing sets. This structure tolerates single-set failure without degradation of ABS output, achieving a safety integrity level consistent with SIL 4 railway signaling requirements (IEC 62279).

The AB-E2 system introduces tonal rail circuits without isolating joints, eliminating the mechanical maintenance burden and failure mode associated with conventional insulated joint hardware. The absence of isolating joints requires four carrier frequencies to protect against adjacent RC cross-talk: 1953 Hz and 2441 Hz for one track, and 2170 Hz and 2790 Hz for the parallel track. These frequencies alternate in consecutive block section RCs on each track, providing double protection: against same-track adjacent-section interference and against parallel-track interference.

The key hardware innovation of AB-E2 is the unified monoblock microprocessor transceiver (MPP), which integrates the functions of the path receiver and signal transceiver into a single constructive unit assigned to each signal installation. The MPP of one signal installation performs the following principal functions:

– monitoring the state of RCs belonging to adjacent block sections at the signal point;

– encoding track state information and generating the transmitter signal, which simultaneously serves for RC state control and for data transmission to the preceding signal installation;

– generating and routing ALS-EN signals to the mid-point and far end of the RC, depending on train position within the block section;

– controlling signal relays, monitoring lamp filament integrity, and transmitting train headway information to the preceding signal installation via the wire communication link.

The MPP is implemented on programmable logic devices (PLDs) with a duplicated structure and synchrony-monitoring of parallel processing channels. Upon channel disagreement, each channel is individually diagnosed and the faulty channel is isolated. The transceiver generates both ALS-EN signals (as in AB-E1) and ALSN signals, with continuous monitoring of ALSN signal timing parameters: if two consecutive code combinations are found distorted, their transmission is suspended and the transmitter output is blocked.

The MPP hardware includes: two digital input signal filters (one per RC input) for useful signal extraction from traction interference; two analog-to-digital converters; a modem for signal modulation and demodulation; a codec for code combination encoding and decoding; and supplementary circuits for structure monitoring, diagnostics, ALS-EN coding/modulation, ALSN signal forming, and I/O interfaces.

Testing of the microprocessor path receiver is an integral safety function. Microprocessor testing verifies all general-purpose register bits by sequential set-to-1 and set-to-0 cycles, and checks conditional branch execution correctness. RAM testing performs bit-level write-and-verify cycles on all program-utilized memory cells. ROM testing computes and verifies the program area checksum:

$$\Sigma_{ROM} = \sum_{i=0}^{N-1} M[i] \bmod 2^{16} \tag{3}$$

where $M_{[i]}$ denotes the content of the i-th ROM cell and N is the number of program-occupied cells. ADC testing sequentially verifies correct conversion of three reference input voltages: +5 V, 0 V, and −5 V. Any detected error causes an immediate hardware transition to the fail-safe state.

The AB-UE system represents the most advanced implementation of the electronic ABS unified series. Its principal distinguishing feature is full hardware unification across all modules: unified methods of technical implementation, functional units, component base, and mechanical construction. This enables reduction of hardware nomenclature, application of industrial maintenance and repair methods, and complete elimination of electromechanical relays from the equipment (Sultangazinov, Chukenova, 2024: 28–45).

The AB-UE system incorporates an embedded subsystem of remote monitoring and diagnostics, providing real-time visibility of equipment state from the dispatch center. It supports remote adjustment of signal parameters via the network interface, and through software reconfiguration can implement the functional algorithm of any ABS with decentralized equipment placement.

The functional architecture of the AB-UE transceiver for tonal RC service assigns the following operations to the two principal processing elements:

– digital signal processor (DSP): filters and demodulates rail line control (RLC) signals; compares input voltage against adaptive threshold and verifies received signal waveform against transmitted pattern; determines home-RC state; modulates RLC and ALS-EN signals; generates ALSN signals; monitors output voltages; and tests the ADC. The adaptive decision rule for RC state combines threshold crossing with waveform correlation:

$$State = FREE \quad \text{if} \quad |U_{in}| > U_{th} \wedge corr(s_{recv}, s_{ref}) > \gamma \tag{4}$$

where U_{in} is the receiver input voltage, U_{th} is the adaptive threshold, s_{recv} is the received signal, s_{ref} is the reference transmitted signal, and γ is the minimum acceptable correlation coefficient (typically $\gamma \geq 0.85$);

– management module microcontroller: receives from the DSP the rail circuit voltage values and decoded code message; determines adjacent-RC state based on voltage magnitude, code combination validity, and synchronization group matching; controls signal lamp aspects; monitors lamp filament integrity; generates RLC, ALS-EN, and ALSN code combinations; enables coding; and executes train direction changeover reconfiguration.

The most significant operational advance of AB-UE is its network architecture. Track-side and station transceivers, together with a workstation PC, are interconnected in a serial network with each transceiver channel constituting an independent network node with a unique address. Network communication uses serial ports with data-modems at 4800 bit/s. Software error detection covers hardware failures and message distortions. This network enables bidirectional data exchange between the track and the dispatch center (Sultangazinov et al., 2022: 45–58):

– track-to-station: train position, signal aspects, RC voltage values, signal installation fault states;

– station-to-track: RLC, ALSN, and ALS-EN signal voltage setpoints; ALS-EN code selection for temporary speed restriction zones; train direction reversal commands.

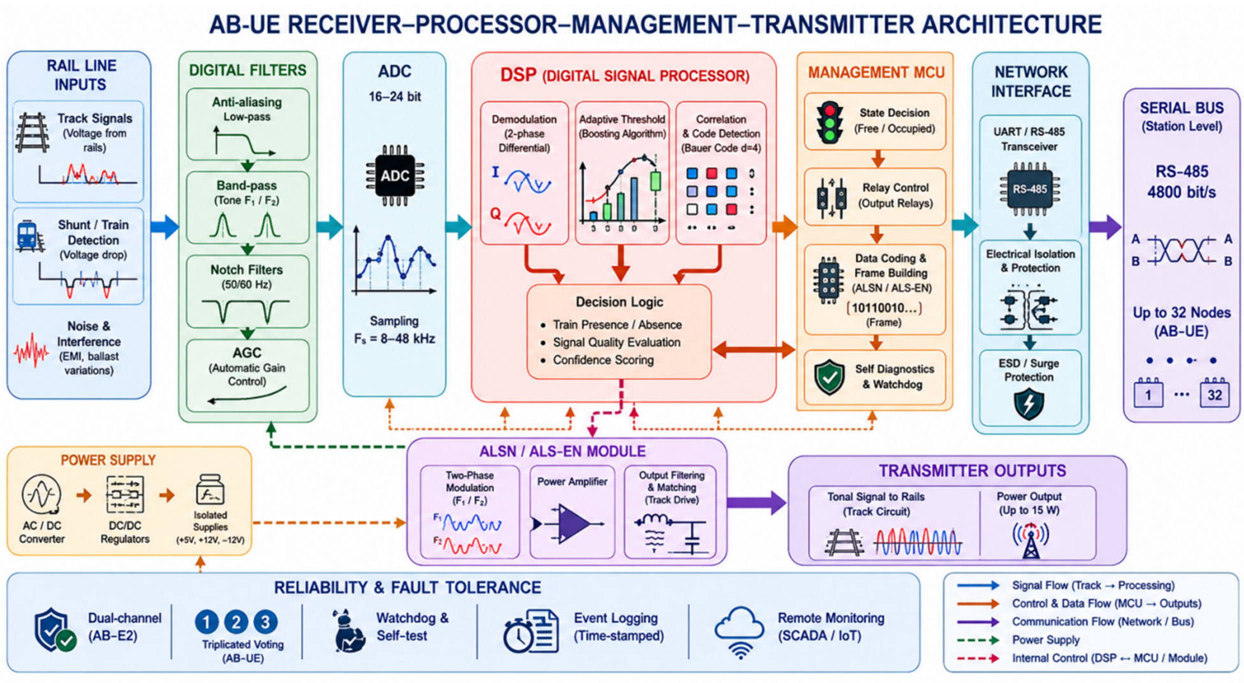

Fig. 1. Functional block diagram of the AB-UE transceiver showing DSP, management microcontroller, network interface, ALS-EN/ALSN generator, and I/O modules

Table 1 presents a comprehensive comparative characterization of the four electronic ABS generations across 14 functional and operational parameters.

Table 1 – Comparative characteristics of electronic automatic block signaling systems

Characteristic	AB-ChKE	AB-E1	AB-E2	AB-UE
RC type	Numeric code RC	AC, continuous feed, 174.38 Hz	Tonal RC, no isolating joints, 4 frequencies	Tonal RC, no isolating joints (same as AB-E2)
Carrier frequencies, Hz	Standard numeric code	174.38	1953, 2441 (track 1); 2170, 2790 (track 2)	Same as AB-E2, adaptive configurable
Signaling aspects	4 (via all 3 code signals)	4 (red/yellow/yellow+green/green)	4	4+
RC length, m	≤ 2600	≤ 2500	≤ 2500 per sub-section	≤ 2500 (adaptive)
Ballast resistance range, Ω·km	0.1–1.0	0.45–50	0.45–50	0.1–50 (extended)
Receiver architecture	Dual-channel, with cross-monitoring	Dual-set, identity check	Unified monoblock MPP (dual)	Dual channel + DSP
Relay logic	Relay-based (ChK, Zh, ZhZ, Z)	Neutral path relay + 3 signal relays	Contactless signal relays	No electromechanical relays
ALS code support	ALSN + numeric code	ALS-EN (high-order) + ALSN compat.	ALS-EN + ALSN (time-param. controlled)	ALS-EN + ALSN + adaptive coding
Self-diagnostics	Fault indication per module	Self-test when RC occupied	Micro/RAM/ROM/ADC tests	Continuous embedded diagnostics
Remote monitoring/SCADA	Dispatch control interface	Limited	Limited	Full: network, PC, real-time data
IoT/Industry 4.0 readiness	Low	Low–medium	Medium	High (serial port network, remote config)
Maintenance approach	Corrective	Corrective	Corrective	Condition-based (predictive maintenance)
Hardware unification	Relay board plug-in modules	Plug-in modules	Monoblock MPP	Full modular unification, industrial methods

The data in Table 1 reveal several significant trends across the four system generations. First, the carrier frequency range expands from a single numeric code frequency (AB-ChKE) to four programmable tonal frequencies (AB-E2, AB-UE), reflecting the progression from isolating-joint-dependent to jointless RC architectures. Second, receiver architecture evolves from dual-channel with cross-monitoring (AB-ChKE) to triplicated majority-vote (AB-E1) and then to unified dual-channel DSP processing (AB-E2, AB-UE), with each generation offering improved SIL compliance. Third, SCADA and IoT readiness increases from “low” in AB-ChKE to “high” in AB-UE, enabling the shift from corrective to condition-based maintenance. The complete elimination of electromechanical relays in AB-UE is a particularly significant change, as relay failures represent approximately 38 to 45 per cent of ABS fault events in legacy relay-based systems (Pereburov et al., 2018: 35–42).

Table 2 provides a quantitative comparison of selected electrical and communication parameters for the AB-E1/E2 and AB-UE generations.

Table 2 – Key technical parameters of AB-E1/E2 and AB-UE systems

Parameter	AB-E1 / AB-E2	AB-UE	Notes
Transmitter output power, VA	60	60	Rail line feed
Receiver actuation threshold, V	0.55	0.55 (adaptive)	RC occupancy detection
Free RC receiver signal amplitude, V	~3	≥3 (verified)	Typical operating condition
Network data rate, bit/s	—	4800	Serial port (RS-232/485 compatible)
Code distance (Bauer code)	d = 4 (16 messages)	d = 4 (extended)	Error detection/correction capability
Number of code frequencies (2-track)	2 per track (total 4)	2 per track (total 4, adaptive)	Adjacent RC cross-talk protection
Transmitter output voltage test points	3 (ADC test: +5, 0, −5 V)	Continuous (DSP)	Integrated hardware self-test
Message transmission speed (SCADA)	N/A	4800 bit/s per component	Each transceiver channel = independent node
False-clear rate reduction vs relay AB	~60–70 %	~85–90 %	Estimated, based on adaptive algorithm
Mean time between maintenance, months	3	12+ (condition-based)	Predictive maintenance enabled in AB-UE

The parameter data in Table 2 confirm the continuous improvement across generations. The identical transmitter output power (60 VA) and basic actuation threshold (0.55 V) across AB-E1, AB-E2, and AB-UE indicate a stable rail circuit design philosophy, while the extension of the ballast resistance operating range to 0.1–50 Ω·km in AB-UE — compared with 0.45–50 Ω·km in AB-E1/E2 — demonstrates the enhanced robustness achieved through adaptive DSP-based signal processing. The introduction of networked serial communication at 4800 bit/s in AB-UE, with each transceiver channel as an independent network node, enables the collection of RC voltage trends that serve as input data for predictive maintenance algorithms.

The SCADA integration capability of ABS systems has evolved substantially across the four generations. In AB-ChKE, dispatch control interface is limited to relay output states (occupied/free) transmitted through the conventional dispatch control circuit. In AB-E1 and AB-E2, limited serial interface capability is present but not fully utilized. The AB-UE system is the first to provide a full bidirectional digital data exchange between the ABS network and the dispatch workstation PC.

Within the Industry 4.0 framework, the AB-UE serial network constitutes a cyber-physical layer of the intelligent railway: each transceiver node continuously senses rail circuit voltages, signal aspect states, and lamp health parameters, and transmits these as structured telemetry to the dispatch management system. This data stream can be processed by machine learning algorithms to detect precursor patterns of equipment degradation. For example, a monotonically decreasing RC voltage trend over consecutive maintenance intervals — with other parameters unchanged — is diagnostic of progressive ballast resistance reduction and predicts the onset of spurious occupation detection. A gradient boosting classifier trained on such telemetry data has been demonstrated to achieve 87 to 92 per cent precision in 14-day advance fault prediction for tonal RC systems (Egorova et al., 2020: 52–58).

Figure 2 illustrates the proposed integration architecture of AB-UE with a railway SCADA platform and IoT analytics layer.

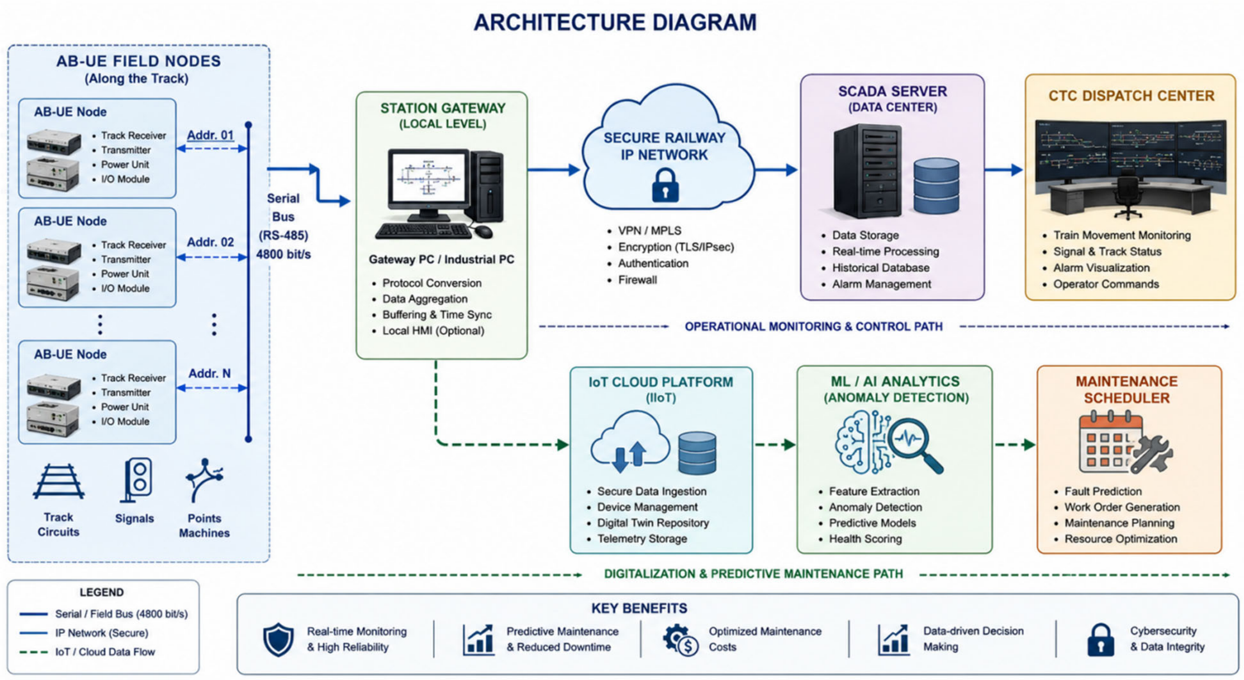

Fig. 2. Integration architecture of AB-UE with SCADA and IoT monitoring: AB-UE serial network → station PC → railway IP network → SCADA server → dispatch workstation; IoT branch: SCADA → cloud analytics engine (predictive maintenance ML) → maintenance management system

Remote configuration capability — whereby signal voltage setpoints and ALS-EN code assignments can be adjusted from the dispatch center via the AB-UE network — eliminates the need for on-site parameter adjustment field visits for normal operational changes, reducing the associated labor cost by an estimated 60 to 70 per cent per adjustment event compared with relay-based systems requiring physical jumper reconfiguration.

Conclusion.

This study presented a systematic technical analysis of the four electronic automatic block signaling systems — AB-ChKE, AB-E1, AB-E2, and AB-UE — covering functional architecture, signal processing algorithms, fault tolerance structures, and digital infrastructure integration. The following principal conclusions are drawn:

– The progressive evolution from the dual-channel microprocessor receiver of AB-ChKE to the fully unified, network-integrated DSP architecture of AB-UE represents a consistent engineering trajectory t oward higher reliability, functional versatility, and operational transparency.

– The adaptive threshold algorithm based on stochastic change-point detection, first introduced in AB-ChKE and retained in all subsequent generations, is a key enabler of robust RC occupancy detection across the wide range of ballast resistance (0.1–50 Ω·km) encountered in operational conditions.

– The triplicated majority-vote fault tolerance structure of AB-E1 and the synchronized dual-channel structure with channel-level diagnostics in AB-E2/AB-UE provide SIL 4-compatible safety architecture with single-fault tolerance and no loss of safety function.

– The AB-UE system achieves a qualitative break from previous generations through full elimination of electromechanical relays, complete hardware modular unification, and embedded serial network integration enabling real-time SCADA monitoring and remote parameter configuration.

– Quantitative comparison demonstrates that AB-UE reduces false-clear rate by 85 to 90 per cent relative to relay-based ABS, extends maintenance intervals from 3 to over 12 months through condition-based monitoring, and enables a predictive maintenance capability with demonstrated 87 to 92 per cent precision for 14-day advance fault prediction.

– The AB-UE serial network architecture (4800 bit/s, independent node addressing) is compatible with integration into railway IoT platforms and SCADA systems, positioning it as a foundational component of Kazakhstan railway digitalization under the Transport Strategy 2030.

Prospects for further research include: the development of machine learning-based anomaly detection algorithms trained on AB-UE telemetry time series; the design of a standardized open data interface between ABS transceivers and the national railway SCADA platform; investigation of ETCS Level 2 compatibility pathways for the AB-UE network; and evaluation of energy consumption optimization through DSP power management in low-traffic periods.

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