



Research article

Blockchain-based inter-operator settlement system

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ABSTRACT

Inter-network settlement is a critical mechanism for ensuring quality service and sustainable growth in the telecommunications industry. However, existing practices among operators suffer from inefficient, including manual workflows, untrustworthy data foundations, insecure dispute resolution, and insufficient accountability oversight. These challenges lead to prolonged settlement cycles, operational redundancies, and heightened risks of errors or leaks. To address these issues, we propose a blockchain-powered settlement chain framework that integrates business and technical systems to enable intelligent, trusted, and automated cross-operator settlement management. By synergizing consortium blockchain, privacy-preserving computation, and decentralized governance protocols, the framework establishes an end-to-end digital workflow covering data exchange, verification, auditing, and reconciliation. Key innovations include: (1) a multi-operator co-built consortium chain with cross-cloud networking and peer-to-peer governance; (2) a “data-available-but-invisible” auditing mechanism combining blockchain and privacy-preserving computation to ensure secure, compliant interactions; and (3) a dynamic chaincode architecture supporting real-time rule synchronization and adaptive cryptographic controls. The framework achieves full-process traceability, automated reconciliation, and enhanced financial governance while reducing reliance on manual intervention. This work provides a transformative paradigm for modernizing telecommunications settlement systems through digital trust infrastructure.

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1. Introduction

Providing trustless solutions, blockchain [1,2] has gained widespread interest in recent years owing to its revolutionary potential across industries. This potential proves pivotal for inter-network settlement [3,4]—a cornerstone of telecommunications collaboration. Smooth and rational inter-network settlement [5] constitutes a fundamental guarantee for the development of the telecommunications industry. To ensure uninterrupted communication among users, operators must establish interconnection [6]. As communication processes consume resources from both interconnected parties, the operator generating user revenue must settle a portion of fees with the counterpart operator, achieving mutual benefits. This mechanism not only safeguards service quality but also fosters industry growth, underscoring the critical importance of effective inter-network settlement in telecommunications. To ensure rigorous and equitable implementation, operators need to establish detailed settlement protocols and dedicate significant human resources to manage settlement workflows.

Current inter-network settlement practices among operators lack scientific rigor and operational efficiency. Despite years of

interconnectivity between operators, critical processes—such as data exchange, email-based verification, manual signature confirmation, and paper-based reporting—remain heavily reliant on human intervention. This manual dependence undermines the timeliness, accuracy, and security of settlements, leading to prolonged cycles, complex workflows, high operational costs, and inefficiency. Key challenges include (1) inadequate trustworthy data foundations, where divergent data granularity standards, inconsistent rule interpretations, and misaligned updates create discrepancies that are difficult to trace, forcing operators to rely on offline paper reports and exacerbating delays; (2) limited secure dispute resolution mechanisms, as manual offline reconciliation (e.g., email exchanges of sampled discrepancies) lacks comprehensive data coverage and root-cause analysis, increasing leakage risks; (3) absence of trust-driven collaboration frameworks, where the coexistence of competition and cooperation necessitates a neutral, consensus-based platform, yet provincial subsidiaries instead invest in redundant bilateral systems or personnel, raising costs without improving efficiency; and (4) lack of accountability oversight, with critical processes like fee adjustments, historical reconciliations, and audit confirmations lacking mutual supervision or traceability, leaving subsidiaries to manually compile error-prone documents and rely solely on stamped settlement results for minimal accountability.

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The integration of digital technologies to safeguard implementation processes represents a strategic direction in settlement management. In the intensely competitive modern society, inter-enterprise collaboration enables organizations to leverage collective strengths, share risks, extend business lifecycles, and enhance operational vitality, thereby securing greater mutual benefits. However, the absence of credible digital systems and capabilities among collaborating entities hinders efficiency improvements, cost reduction, and the advancement of deeper partnerships. The inter-network settlement among operators exemplifies a typical cross-enterprise integrated business scenario. Yet, both its implementation philosophy and supporting mechanisms have proven inadequate in addressing increasingly complex settlement management requirements. The rapid evolution of digital technologies now offers innovative solutions to modernize settlement processes—replacing manual workflows with automated systems, establishing robust trust mechanisms, and providing more scientific methodologies, trustworthy data, and streamlined procedures—thereby facilitating the scientific implementation of inter-network settlements. While emerging technologies present dual challenges and opportunities, operators must seize this momentum to comprehensively innovate online settlement processes and ensure high-quality execution of inter-network settlement practices.

We propose a settlement chain that synergizes business and technical dual systems to drive transformative advancements in intelligent settlement management. The framework establishes a cross-operator end-to-end trusted settlement management system, enabling integrated digital operations for cross-domain services. It constructs a fully online workflow encompassing data exchange, verification, confirmation, auditing, payment, and reconciliation while innovating a blockchain-based inter-network settlement architecture to achieve precise, efficient settlements and enhanced governance efficacy. Additionally, it develops cross-operator trusted technical capabilities to provide foundational support for collaborative digital operations.

- The settlement chain achieves systematic innovation through a joint operational platform that enables full-process digitalization and standardized management. It automates reconciliation and secure auditing via privacy-preserving computation, while an integrated electronic signature system ensures end-to-end traceability and financial control.
- As the first multi-operator co-built consortium chain, the settlement chain pioneers peer-to-peer governance based on cross-cloud networking and unified protocols. By integrating blockchain with privacy-preserving computation, the settlement chain constructs a “data-available-but-invisible” closed-loop auditing framework, fulfilling stringent security requirements through encrypted data interactions and real-time rule synchronization.
- Our framework ensures transparent and traceable rules via cross-cloud networking and smart contracts, while privacy-preserving computation enforces compliance through circuit-breaker mechanisms and data anonymization. Its decentralized chaincode architecture supports dynamic scalability, and the adaptive national cryptographic standards enhance transaction security, establishing a trusted ecosystem with balanced accountability and full-chain controllability.

2. Related work

Interconnection Settlement in Telecommunication Networks. Telecommunication interconnection settlement serves as a critical mechanism for ensuring quality and fairness across operator networks, requiring coordinated technological, economic and

policy approaches. Studies by Li et al. [3] reveal persistent cost allocation challenges stemming from traffic asymmetry in China’s Internet backbone, a common issue in IP networks [7]. To address this, Zhang et al. [4] developed dynamic pricing models using regression analysis, while blockchain-based smart contract systems [8] and infrastructure reuse strategies [9] offer innovative technical solutions. Regulatory frameworks play an equally vital role, with Zhao et al. [10] emphasizing the need to balance competition and cooperation among operators. Lin et al. [11] demonstrate how incentive mechanisms can effectively coordinate market power, particularly in complex scenarios like cross-border interconnections [12] or heterogeneous network environments requiring QoS-cost balancing [13]. The practical implementation relies on robust auditing systems to monitor settlements and prevent revenue leakage [14]. Blockchain plays a crucial role in the settlement of interconnections. Xu et al. [15] propose a blockchain-enabled metaverse architecture using hypergraph-based trust models and on-demand trusted computing for secure resource allocation. Guo et al. [16] propose zkCross, a two-layer architecture enabling privacy-preserving cross-chain operations and efficient auditing via zero-knowledge proofs.

Data Management and Security. In the field of multi-organizational telecommunications, effective data governance and security mechanisms form the foundation for cross-institutional collaboration and regulatory compliance. Otto et al. [17] establishes that successful data governance requires well-defined organizational structures with clear accountability across departments. This framework is expanded by Yi et al. [18] through their three-tier “policy-technology-monitoring” model, while Alhassan et al. [19] demonstrates the critical balance between data sharing and privacy protection in telecom operations. Xu et al. propose SPDL [20], a blockchain-based decentralized learning framework combining BFT consensus, gradient aggregation, and differential privacy to ensure security, privacy, and Byzantine resilience without trusted servers. From a technical perspective, the proliferation of big data and IoT applications introduces complex security challenges. Kastouni et al. [21] proposes integrating governance modules throughout the data lifecycle, complemented by Al et al.’s [22] analysis of topological vulnerabilities in multi-party data exchanges. For secure data transfer, Yang et al. [23] develops an innovative optical-based solution, with Tyagi et al. [24] advocating zero trust architectures as essential for modern network defense. Liu et al. [25] propose a TEE-based framework integrating blockchain to extend on-chain trust to off-chain vaccine tracing, ensuring tamper-proof data collection and real-time consistency. Industry implementations reveal evolving requirements, particularly in IoT/5G environments [26]. Li et al.’s [27] early insights into cloud-network convergence remain highly relevant. Future research could focus on optimizing multi-party data collaboration governance through federated learning, blockchain-enabled decentralized data authentication, and adaptive upgrades of generative AI for data security defense systems.

3. System framework

3.1. Design objectives

Guided by the principles of trusted technology sharing, secure data interoperability, and co-utilization of capabilities, we develop a settlement chain—a blockchain-powered cross-domain settlement platform—to innovate secure and transparent settlement mechanisms. This initiative addresses systemic challenges in inter-operator collaboration, including the absence of trusted operational drivers, insecure data foundations, unverifiable accountability oversight, and inefficient dispute resolution, thereby enabling secure, compliant, and high-efficiency settlement management through fully digitized solutions.

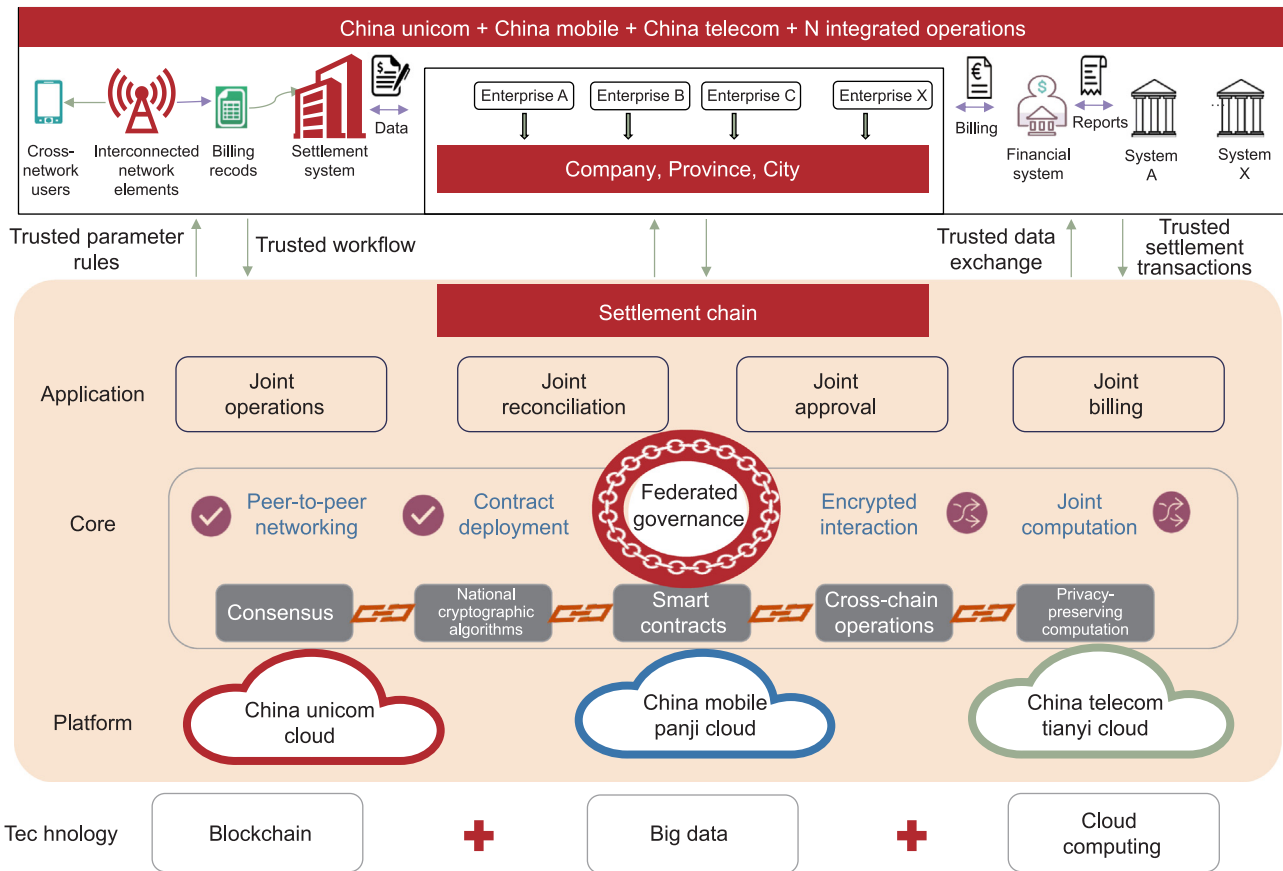


Fig. 1. Framework of settlement chain.

Leveraging inter-network settlement as a pivotal entry point, the three operators integrated big data, blockchain, and cloud computing to establish unified technical standards for trusted joint operations. The settlement chain platform dismantles data silos, mitigates risks of leakage, tampering, and disputes, and pioneers a new paradigm for equitable, regulation-compliant, controllable, and trusted collaboration within the telecommunications industry. By standardizing transparent rules, operational workflows, and secure data interactions, it fosters ecosystem innovation and constructs a digital settlement service ecosystem characterized by accuracy and interoperability.

To advance the secure compliance and efficiency of inter-operator interconnected settlement services, this initiative addresses critical challenges including the lack of trusted drivers for collaborative workflows, insecure foundations for data interoperability, unverifiable oversight mechanisms for operational accountability, and inadequate dispute resolution capabilities. By co-establishing a consortium blockchain tailored to five business operation scenarios, the framework develops two core capabilities

—trusted governance protocols and privacy-preserving automated reconciliation—alongside four jointly operated trusted applications. This integrated approach drives the digital transformation of cross-operator settlement processes, ensuring standardized, transparent, and auditable operations while systematically resolving historical bottlenecks in multi-party collaboration.

Implementation Roadmap:

- **Phase 1 (2022):** We developed distributed peer-to-peer networking based on blockchain, preliminarily establishing the settlement chain platform for the interoperability of trusted

data. The operators co-designed a joint settlement management application deployed across 10 provincial branches, achieving decentralized smart contract governance and improved transaction efficiency through visual contract management.

- **Phase 2 (2023):** Another operator joined the settlement chain via peer-to-peer networking, enabling tripartite collaboration. Coverage expanded to 25 provinces for joint reporting, while automated reconciliation and privacy-preserving computation capabilities were developed for cross-operator detailed billing data audits.
- **Phase 3 (2024):** China Broadcasting Network (CBN) integrated into the platform, extending quadripartite collaboration. Joint billing approval and automated payment reconciliation systems with e-signatures were implemented, achieving end-to-end settlement digitization.
- **Phase 4 (2025):** The settlement chain will evolve into an open ecosystem, enabling cross-industry collaborations such as 5G internetwork roaming settlements, IoV (Internet of Vehicles) roaming billing, and multiparty partner settlements, fostering converged digital operational capabilities.

3.2. Platform architecture

As shown in Fig. 1, leveraging the existing foundational capabilities in cloud computing, network infrastructure, blockchain, and data platforms of multiple participants, we establish a block chain-based cross-operator settlement platform from the consortium, Settlement Chain, under unified standards and protocols. Designed to serve five critical business scenarios—joint online operations, shared rule governance and public parameter

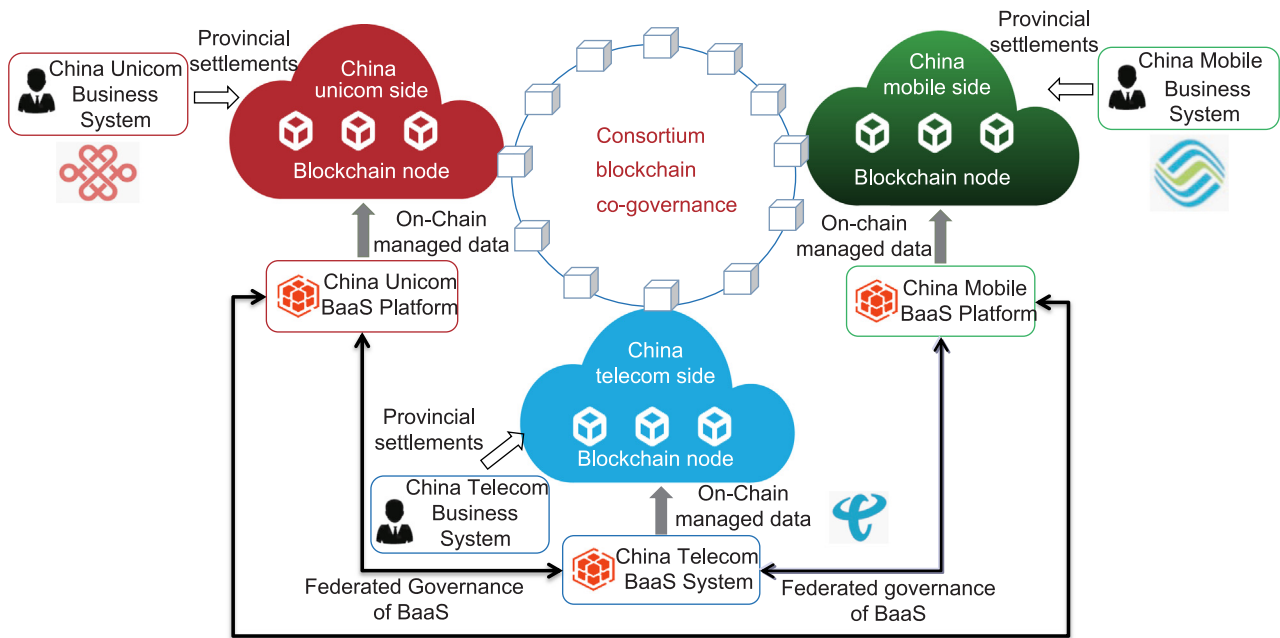


Fig. 2. Federated governance architecture of the settlement chain.

verification, collaborative discrepancy analysis, unified billing approval, and automated reconciliation—the platform integrates blockchain BaaS (Blockchain as a Service) for distributed federated governance and privacy-preserving computation technologies. By developing four integrated applications—distributed joint settlement management, automated reconciliation management, collaborative approval management, and unified billing management—it enables seamless three-tier collaboration (group, provincial, and municipal levels) across operators, driving comprehensive digital transformation through standardized workflows, secure data interactions, and auditable multi-party accountability.

3.3. Core capabilities of the settlement chain

As shown in Fig. 2, the blockchain distributed federated governance platform enables China Unicom, China Mobile, and China Telecom to jointly operate a consortium blockchain for cross-operator coordination. Built on Hyperledger Fabric, it integrates decentralized BaaS cross-cloud networking and multi-national cryptographic compatibility, allowing each operator to deploy proprietary nodes (e.g., Unicom Chain) within their own cloud environments while ensuring equal governance. The platform supports federated BaaS governance, synchronizes on-chain data like provincial settlements, and enables interoperability through unified protocols, addressing security and auditability in critical operations such as inter-provincial settlements and cross-network service verification.

The federated governance model balances autonomy and collaboration: operators independently manage their BaaS platforms and nodes while adhering to shared protocols. For instance, China Telecom's system interacts with other operators' nodes via standardized smart contracts, ensuring consistent settlement rule execution. By bridging provincial settlement centers and on-chain data, the platform automates reconciliation and provides real-time transaction visibility. Combining decentralized control with centralized standards, it resolves challenges like inter-provincial roaming fee reconciliation and IoT settlements while maintaining compliance, setting a benchmark for scalable blockchain governance in regulated sectors.

As shown in Fig. 3, the settlement chain functions as a distributed privacy-preserving computation platform, designed for large-scale automated discrepancy analysis. Key participants deploy privacy-preserving computation modules within their respective cloud infrastructures (Unicom Cloud, Panji Cloud, and Tianyi Cloud). Integrated with blockchain and smart contracts, the platform employs a proprietary trusted reconciliation engine that facilitates real-time scheduling of reconciliation tasks and dynamic rule synchronization across stakeholders. Standardized interfaces enable granular data extraction from production systems while implementing cryptographic techniques such as data anonymization and private set intersection. These capabilities achieve “usable-yet-invisible” data sharing, ensuring compliance with strict data localization requirements and resolving cross-domain security challenges.

3.4. Core application capabilities of the settlement chain

Fig. 4 illustrates an integrated blockchain-based settlement system collaboratively developed by major Chinese telecom operators (China Unicom, China Mobile, and China Telecom). It showcases four core applications working in tandem with frontend interfaces, financial services, and cross-BaaS governance infrastructure to enable secure, transparent inter-operator settlements across scenarios like 5G roaming and IoT services.

The joint settlement workflow management application serves as the core platform for cross-operator financial interactions, governing the complete settlement lifecycle through smart contracts that automate processes from data exchange to final approval. By embedding business logic into tamper-proof blockchain code, it ensures trusted execution across operators while certifying critical parameters like settlement rules and operational directives. The system extends beyond automation by implementing cryptographic verification for standardized data—including public parameters and consortium agreements—to create a transparent, auditable framework. This dual focus on process automation and data integrity eliminates manual errors and disputes while ensuring compliance, significantly advancing settlement efficiency and reliability.

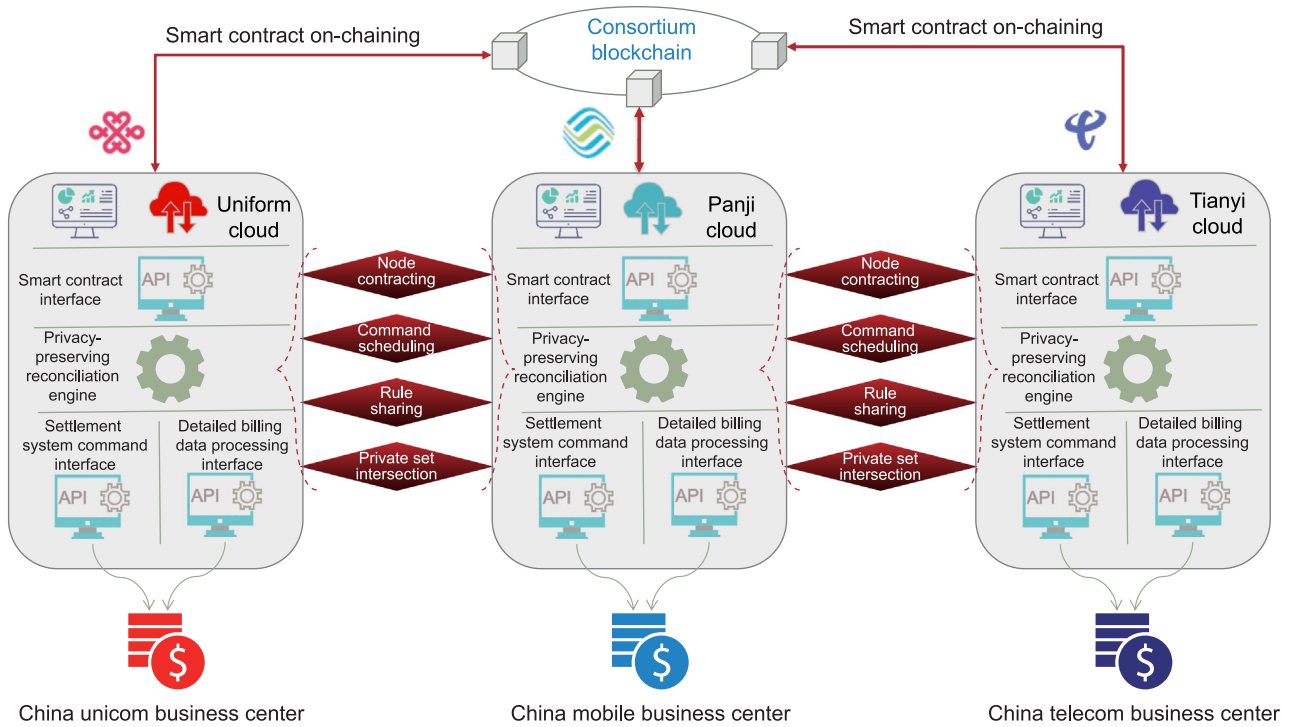


Fig. 3. Privacy-preserving reconciliation architecture of the settlement chain.

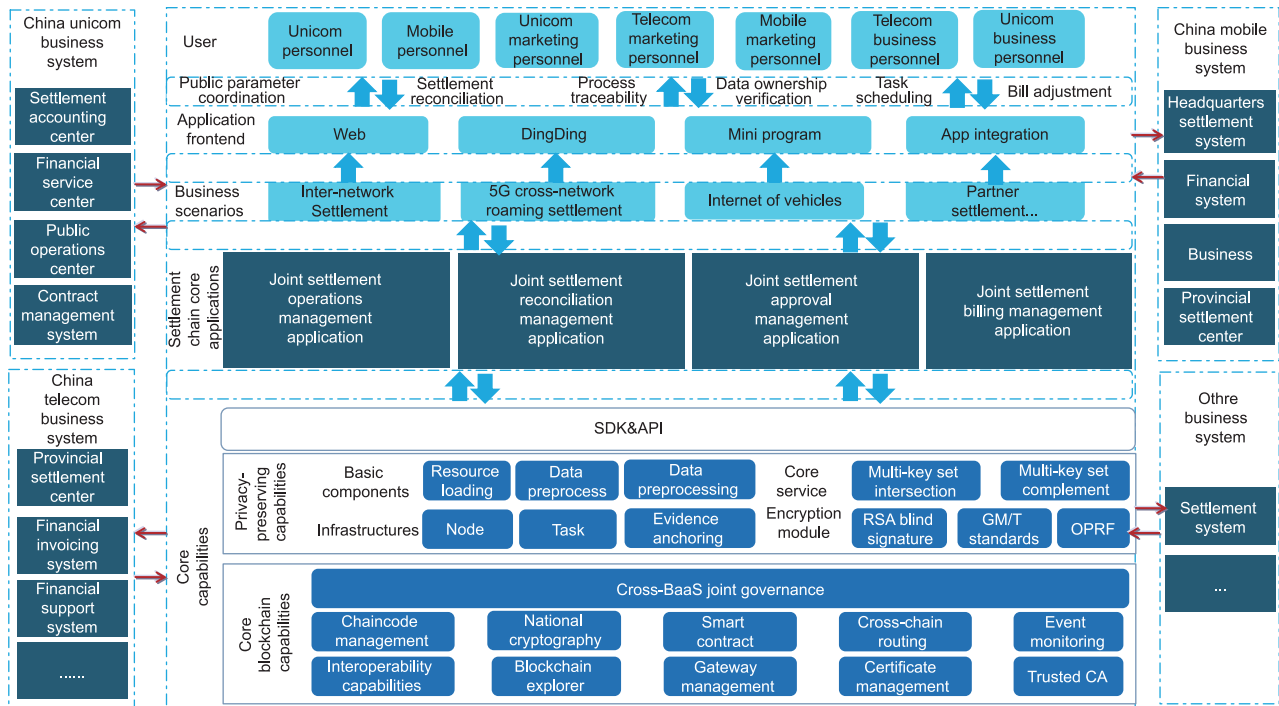


Fig. 4. Architecture of the settlement chain's application capabilities.

At the heart of dispute resolution sits the joint settlement reconciliation management application, which revolutionizes how operators handle discrepancies through its sophisticated combination of federated privacy-preserving computation and a next-generation trusted reconciliation engine. It employs cryptographic techniques like multi-key set operations (intersection/complement) and GM/T-standard protocols to analyze discrepancies

while ensuring data confidentiality. The system enables rapid automated reconciliation, mutual audit scope agreements, and report generation, reducing manual processing from days to hours. Critical for high-stakes scenarios like 5G roaming settlements, it balances on-chain transparency for accountability with robust off-chain privacy measures to protect commercial data, redefining standards for inter-operator financial reconciliation.

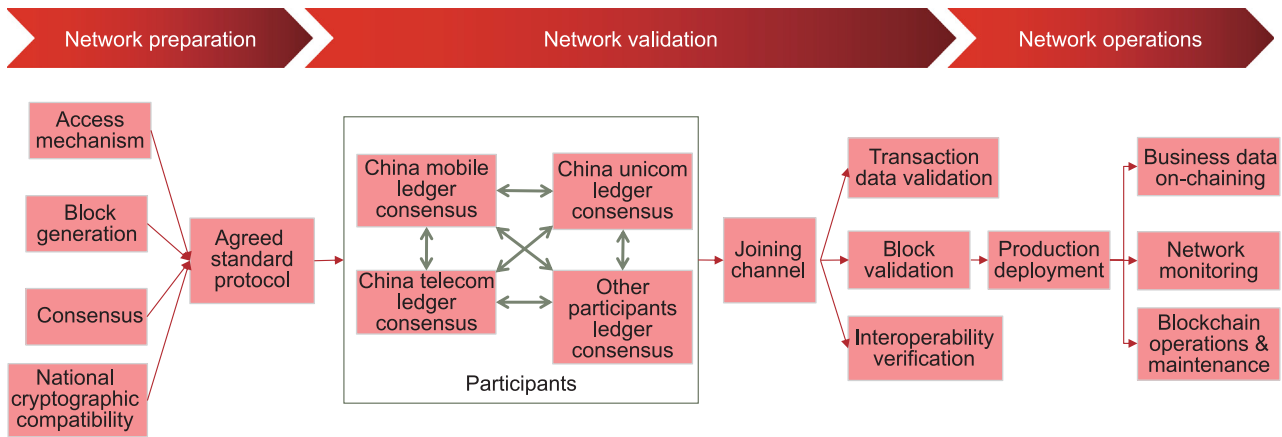


Fig. 5. Process of distributed peer-to-peer networking in consortium blockchain.

Transforming authorization processes for the digital age, the joint settlement approval management application revolutionizes authorization processes by anchoring metadata hashes and legally-binding e-signatures to blockchain, creating an immutable verification layer integrated with systems like DingDing. This enables real-time authentication between operators' departments—such as cryptographic signing of billing adjustments between China Telecom's marketing and China Unicom's finance teams—with every step permanently recorded. By eliminating paper-based delays and forgery risks, it generates regulator-ready audit trails while ensuring compliance and preventing document tampering, fundamentally transforming settlement approval workflows.

Completing the settlement ecosystem, the joint settlement billing management application bridges blockchain settlements with traditional financial systems, automating the entire billing lifecycle from submission to archival. Upon finalizing digitally signed settlement documents, the system integrates with operators' invoicing systems and settlement centers to track real-time payment statuses. It continuously monitors account aging, receivables, and cash flows across all participants, deploying intelligent alerts to flag overdue transactions—such as unresolved inter-network roaming fees—for immediate resolution. This ensures synchronized financial oversight across organizations. Crucially, the application demonstrates blockchain's seamless integration with legacy financial infrastructure, achieving true interoperability without compromising auditability—a breakthrough critical for complex, large-scale implementations like IoT fleet settlements and multi-carrier 5G revenue sharing, where efficiency and transparency are paramount.

4. Technical design

4.1. Novel cross-operator infrastructure

The workflow outlined in Fig. 5 describes a comprehensive blockchain-based framework designed for multi-operator collaboration. The process begins with network preparation, where participating operators deploy an equal number of blockchain nodes within their respective cloud environments. These nodes are uniform in status and functional roles, ensuring a balanced and decentralized architecture. Key components of the workflow include the implementation of peer consensus mechanisms (e.g., China Mobile Ledger Consensus, China Unicom Ledger Consensus), block generation policies, and access control protocols, all of which are either self-developed or configured to meet

specific requirements. The system also adheres to national cryptographic standards and interoperability verification to ensure security and seamless integration across different operators.

Once the network is established, it undergoes rigorous validation, including transaction data validation, block validation, and interoperability checks. The validated blocks are then added to a unified distributed ledger, collaboratively maintained by all participants. This ledger serves as the foundation for cross-operator business integration, enabling secure and transparent data sharing. The final stages of the workflow focus on production deployment, where business data is formally on-chained, and ongoing network monitoring and blockchain operations & maintenance are performed to ensure system stability and reliability. This framework not only facilitates secure peer-to-peer networking but also supports scalable and interoperable blockchain solutions for multi-operator environments, paving the way for advanced business applications and collaborative innovations.

The workflow, as shown in Fig. 6, illustrates a heterogeneous BaaS (Blockchain-as-a-Service) platform designed for multi-party governance in a consortium blockchain environment. Adopting a "blockchain-governs-blockchain" approach, the system establishes a shared management channel where participants jointly deploy governance smart contracts and maintain a distributed governance ledger. This framework enables real-time synchronization of critical operations, including channel management, chaincode upgrades, node administration, and membership controls across diverse BaaS platforms. Governance decisions follow a decentralized voting mechanism: requests (e.g., contract deployments or link configurations) are broadcast, voted on by BaaS nodes, and executed only upon approval, with all actions immutably recorded on-chain for auditability.

The system supports dynamic organization onboarding and seamless cross-BaaS coordination, making it ideal for industry consortia, financial networks, and regulated ecosystems. By embedding governance logic into smart contracts, it eliminates manual intervention, reduces disputes, and maintains a tamper-proof record of consortium activities. The integration of national cryptographic standards and interoperability protocols further ensures secure, scalable collaboration across heterogeneous environments, paving the way for standardized blockchain adoption in multi-stakeholder scenarios.

4.2. Cross-operator collaborative settlement operations

To enhance the quality and efficiency of collaborative operations, the consortium blockchain, as illustrated in Fig. 7, jointly established by operators enables end-to-end settlement workflows.

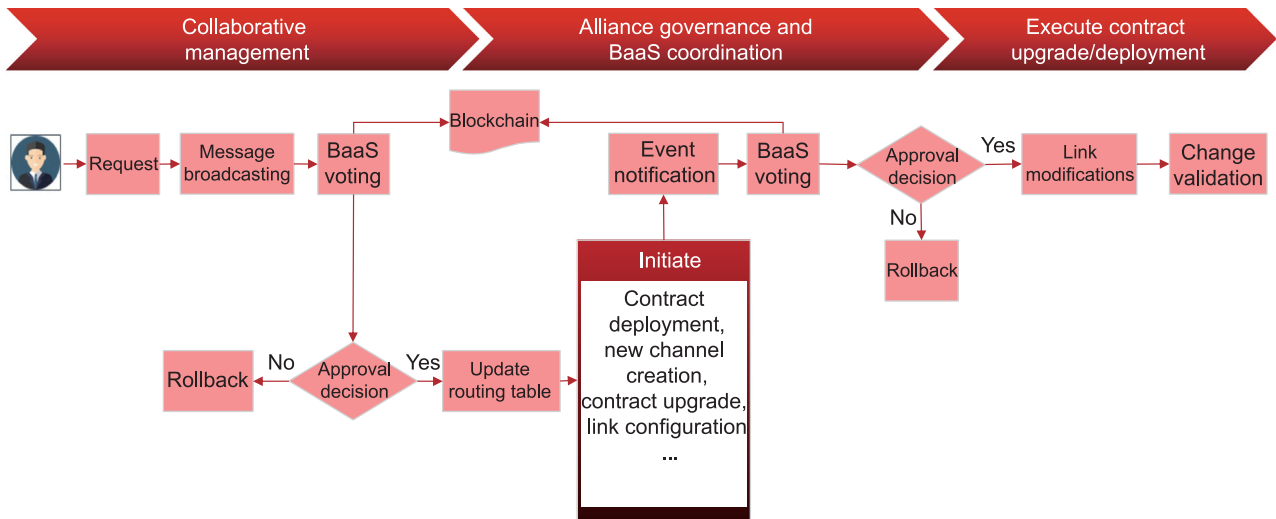


Fig. 6. Workflow of distributed peer management in consortium blockchain.

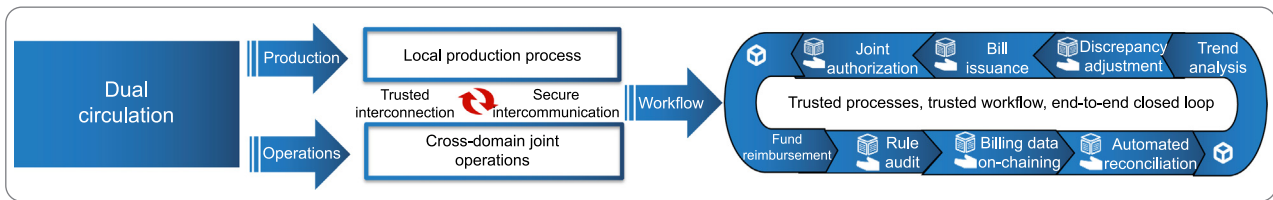


Fig. 7. End-to-end closed-loop process of cross-entity settlement.

Four integrated applications and on-chain smart contracts connect BSS/MSS operational systems—including headquarters/provincial settlement centers, business support platforms, financial shared services, tax invoicing systems, enterprise resource planning (ERP), and contract management systems. This infrastructure supports closed-loop management of foundational data coordination, joint operations, privacy-preserving reconciliation, approval authorization, and financial reimbursement.

Firstly, as shown in Fig. 8, we present a comprehensive collaborative control capability for blockchain-based settlement systems, establishing a structured three-phase workflow to optimize reconciliation processes. In the initial phase, participating operators collaboratively define standardized settlement parameters and governance rules. The system then implements a dual-validation mechanism where transaction data is first uploaded to the blockchain and subsequently verified by all counterparties, ensuring data integrity through distributed consensus. The final phase leverages smart contracts to automate the reconciliation process and generate tamper-proof settlement records.

This innovative framework delivers significant operational improvements by: (1) ensuring end-to-end transparency through immutable blockchain records; (2) enhancing processing efficiency by reducing manual reconciliation efforts; and (3) establishing cryptographic trust through verifiable consensus at each process stage. The solution's modular architecture not only supports regulatory compliance requirements but also demonstrates potential for broader applications in cross-border trade and supply chain finance, where secure and efficient multi-party settlement is critical. The research highlights how blockchain technology can transform traditional financial reconciliation by combining automation with robust audit capabilities.

Secondly, as shown in Fig. 9, we present an end-to-end cross-domain joint online operations framework that implements a

standardized blockchain-based workflow from billing to settlement confirmation. The system utilizes smart contracts to automate the entire process: after both parties encrypt and upload billing data to the blockchain following unified specifications, the platform executes synchronized decryption, automated item matching, discrepancy analysis, and adjustment calculations. Key components include cryptographic protection of sensitive data, automated interface triggers for review processes, and systematic handling of historical ledger adjustments when discrepancies are detected. This approach eliminates traditional manual reconciliation efforts while ensuring tamper-proof data integrity throughout the settlement lifecycle – from initial data upload through final confirmation. The workflow's decision nodes (e.g., discrepancy checks and historical adjustment requirements) demonstrate how smart contracts can replicate complex business logic while maintaining operational transparency.

Thirdly, as shown in Fig. 10, we present an end-to-end closed-loop management system that ensures settlement security and compliance through blockchain-based automation. The framework establishes a complete digital workflow from mutual approval to payment reconciliation, featuring three core components: (1) on-chain data anchoring where electronic bills, e-signatures, and payment results are cryptographically secured on the blockchain; (2) enterprise system integration that connects with approval systems and financial platforms for automated tax verification, ERP posting (e.g., General Account updates), and payment status synchronization; and (3) multi-party collaborative verification involving both China Unicom and collaborating parties in audit and e-signature processes.

The solution achieves full process digitization through key innovations: automated invoice entry eliminates manual data transfer errors, while blockchain's immutable ledger provides audit trails for every transaction from billing to fund payment. By anchoring the entire revenue-expenditure cycle on-chain –

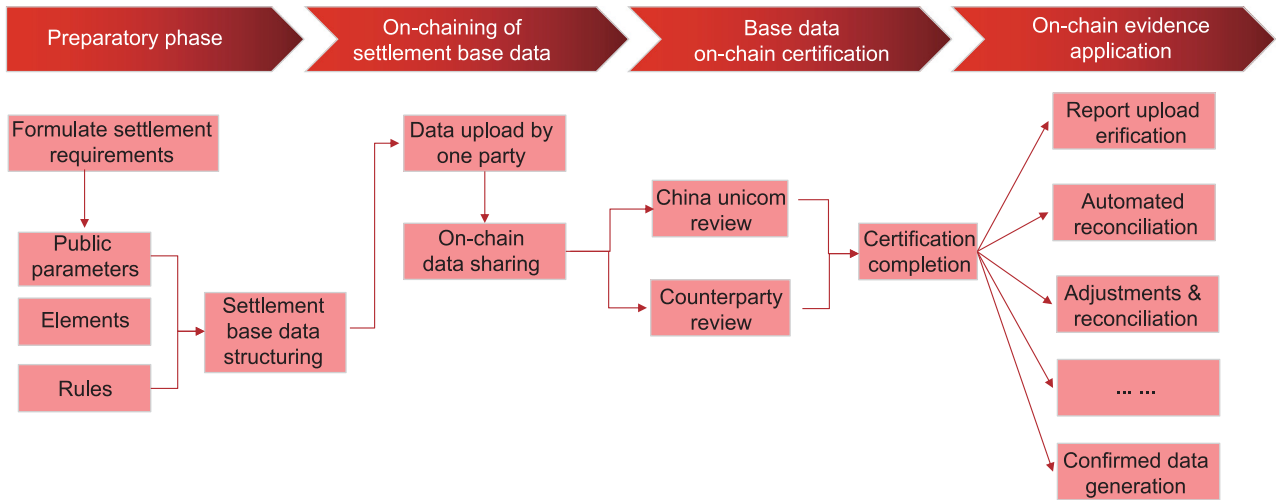


Fig. 8. Workflow of collaborative management for cross-entity settlement elements.

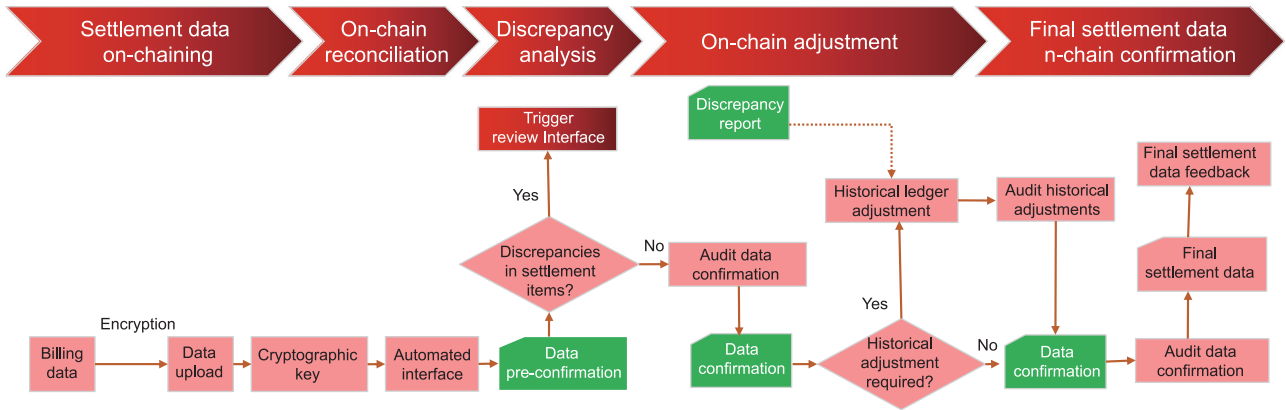


Fig. 9. Process of cross-domain joint online operations.

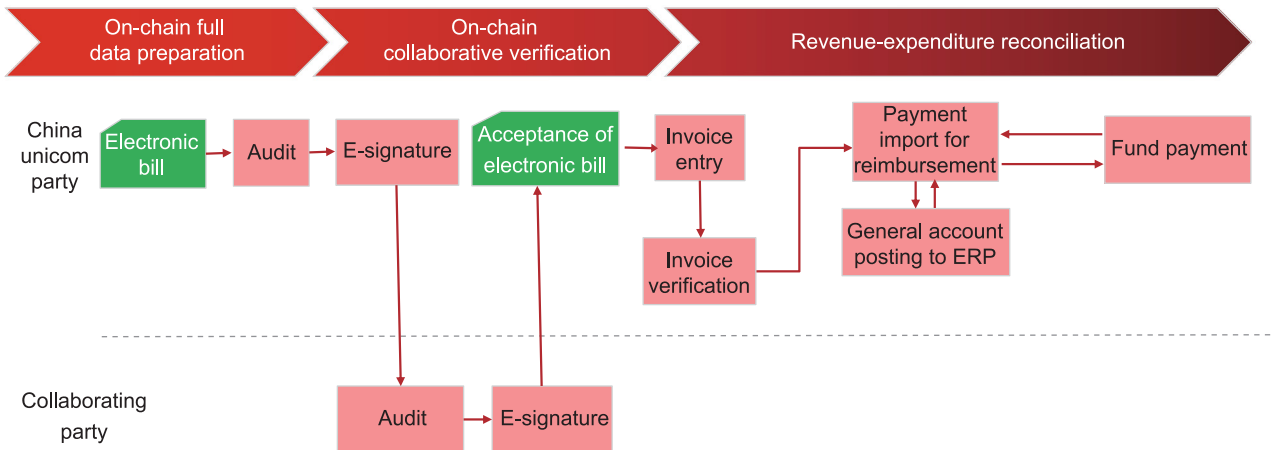


Fig. 10. Trusted closed-loop management process of settlement income-expenditure.

including electronic bill acceptance, reimbursement payment imports, and final account postings – the system guarantees fiscal closure while reducing settlement time compared to traditional paper-based processes. The integrated approach demonstrates how distributed ledger technology can bridge organizational silos between approval systems, financial platforms, and ERP systems without compromising compliance requirements.

Fourthly, as shown in Fig. 11, we present a federated privacy reconciliation framework that combines blockchain with privacy-preserving computation to enable secure cross-operator settlement while maintaining strict data confidentiality. The system initiates with bilateral audits of detailed billing records extracted from production systems, which undergo anonymization before processing on a privacy-preserving computation platform.

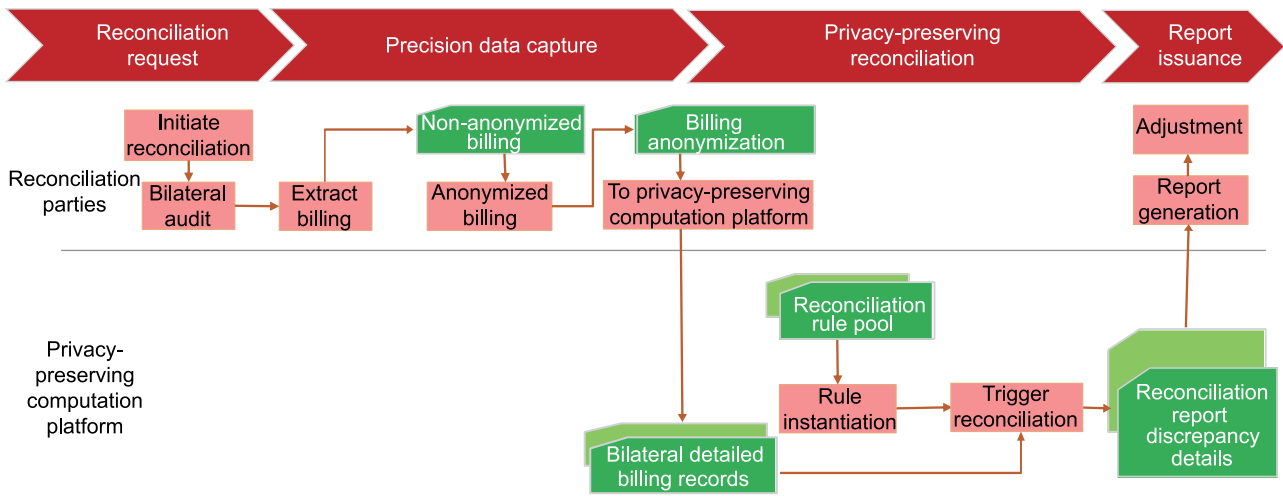


Fig. 11. Federated privacy-preserving reconciliation workflow for cross-operator systems.

Through hybrid reconciliation rules incorporating both common standards and customized parameters, the platform performs encrypted cross-party audits using techniques like range validation and private set intersection. All reconciliation reports and discrepancy details are securely anchored on the blockchain, creating immutable audit trails while preserving data privacy. This innovative approach achieves mathematically-verifiable settlement outcomes with minimized disputes, establishing a trusted foundation for precision collaboration between operators without requiring raw data exposure.

Privacy-preserving computation ensures end-to-end data protection through a multi-layered security framework. First, data encryption and decryption techniques safeguard privacy during transmission and processing. Second, tailored for two-party reconciliation scenarios, a non-conventional secret-sharing mechanism is employed: intermediate computations are performed in a privacy-preserving environment, where irrelevant data fragments are conditionally filtered, fragmented, and masked (e.g., zeroized) to enable accurate discrepancy identification without exposing raw data. Third, security protocols such as key exchange and digital signatures guarantee data integrity and tamper resistance. Within a multi-party collaborative framework, privacy-enhancing technologies like private set intersection swiftly filter consistent and inconsistent transaction records, while secure multi-party computation processes encrypted reconciliation amounts to generate settlement discrepancy reports. This workflow adheres to the “data-available-but-invisible” principle, enabling secure joint analysis across stakeholders while ensuring zero leakage of sensitive information.

5. Analysis

5.1. Economic impact analysis

The assessment of economic benefits serves as a critical lens to evaluate the tangible impacts of technological and procedural advancements in industrial operations. By quantifying improvements in efficiency, cost savings, and risk reduction, such analysis not only validates the return on investment but also provides actionable insights for optimizing resource allocation and fostering sustainable business practices. In the context of cross-operator settlement systems, these metrics underscore the transformative potential of intelligent automation and process standardization.

The shift from manual to regularized settlement operations drastically enhanced efficiency, reducing reconciliation cycles

from weeks to days and achieving significant improvements in operational speed. This optimization resulted in substantial labor savings across routine tasks and exception handling, translating to direct cost reductions. Beyond immediate financial gains, the integration of intelligent systems streamlined management workflows, reinforcing long-term scalability and cost-control capabilities.

Process restructuring and automation significantly bolstered data accuracy and operational reliability. By eliminating redundant workflow steps, manual data transfers and entries were markedly reduced. Automation covered a significant portion of on-chain processes, standardizing execution while mitigating risks of human error, data tampering, and leakage. Automated verification mechanisms further minimized billing discrepancies between parties to near-zero levels, delivering notable annual savings. These improvements stabilized financial operations and enhanced stakeholder confidence in settlement outcomes.

The deployment of distributed applications, including joint settlement management and digital approval systems, accelerated payment cycles by a substantial margin annually. This reduction in delays eliminated a significant volume of overdue receivables, alleviating capital occupation costs and improving cash flow predictability. The shortened cycles not only enhanced liquidity for participating entities but also demonstrated how digitization addresses systemic inefficiencies in transaction-heavy industries. Collectively, these outcomes highlight the synergy between operational innovation and economic resilience, offering a blueprint for similar sectors seeking to balance cost efficiency with financial stability.

5.2. Social impact analysis

The evaluation of social benefits is essential to understanding the broader societal and industrial impacts of technological innovations beyond purely economic metrics. By examining advancements in collaboration models, technological standardization, operational adaptability, and environmental stewardship, such analysis highlights how systemic improvements foster inclusive growth, regulatory alignment, and sustainable development. In the context of blockchain-enabled settlement systems, these benefits demonstrate the symbiotic relationship between technological progress and societal value creation.

The initiative aligns with China's new infrastructure strategy by establishing the nation's first equitable telecom settlement consortium blockchain. This model prioritizes compliance, controllability, and trust in cross-operator collaboration, setting a

precedent for transparent and fair inter-organizational partnerships. By pioneering a standardized framework for blockchain adoption, it not only addresses historical inefficiencies in telecom settlements but also inspires cross-sector replication, fostering a culture of shared infrastructure and cooperative governance in digitally driven industries. Technological innovation was further amplified through contributions to the development of national standards, including the technical requirements for blockchain-based inter-network settlement of the Ministry of Industry and Information Technology (MIIT) and the Chinese Academy of Information and Communications Technology (CAICT) Cross-Operator Blockchain Settlement Specifications under the Trusted Blockchain Initiative (TBI). These standards accelerate the integration of blockchain technology into industrial ecosystems, enhancing its infrastructure value while promoting interoperability and scalability. Such efforts position blockchain as a cornerstone for digital transformation, driving sector-wide adoption and technological maturation.

The framework's agility enables rapid adaptation to emerging demands, such as 5G cross-network roaming and multi-party partner settlements. By forming a high-value interconnected settlement network, it supports ecosystem-wide operational capabilities, creating a unified digital service ecosystem. This scalability ensures that the system remains responsive to evolving market needs, reducing fragmentation and enhancing service delivery efficiency across diverse use cases. Environmental sustainability was advanced through full digitalization of settlement processes, eliminating paper-based workflows in accordance with China's dual carbon goals. By replacing tens of millions of printed documents annually, previously required for mailing and archiving, the initiative significantly reduced resource consumption and carbon emissions. This shift not only supports global climate objectives but also underscores the role of digital innovation in reconciling industrial growth with ecological responsibility, setting a benchmark for green transformation in high-transaction industries. Collectively, these social benefits illustrate how strategic technological integration can catalyze industry-wide collaboration, regulatory coherence, operational resilience, and environmental accountability, ultimately contributing to a more equitable and sustainable digital economy.

6. Conclusion

In this paper, we introduce a novel settlement chain framework that synergizes business-logical and technical systems to advance intelligent cross-operator settlement management. By establishing an end-to-end trusted settlement ecosystem, the framework enables seamless digital operations for cross-domain services through a fully online workflow covering data exchange, verification, auditing, payment, and reconciliation.

Future research could extend the framework's adaptability to emerging technologies such as AI-driven predictive settlement analytics and quantum-resistant cryptography. Expanding its application to multi-industry ecosystems (e.g., cross-border payments, IoT-enabled supply chains) would test its scalability under heterogeneous regulatory environments.

CRediT authorship contribution statement

Shifu Zhang: Software, Conceptualization, Methodology, Supervision, Writing – review & editing. **Yulin Pan:** Software, Validation, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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