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Original Article

Blockchain-Enabled Secure Industrial IoT Architecture for Smart Engineering Applications

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ABSTRACT

Industry 4.0 has accelerated the adoption of the Industrial Internet of Things (IIoT), enabling intelligent communication among industrial devices, edge systems, and cloud platforms for smart manufacturing. However, conventional centralized security approaches are increasingly vulnerable to cyber threats, data tampering, and single-point failures. This paper proposes a secure blockchain-enabled IIoT architecture that integrates industrial sensing, edge computing, distributed ledger technology, cloud analytics, and intelligent decision-making. The framework employs device authentication, encrypted communication, decentralized consensus, smart contracts, and machine learning-based anomaly detection to enhance data integrity, secure information sharing, and cyber resilience. Experimental evaluation demonstrates improvements in communication security, authentication accuracy, transparency, scalability, latency, and throughput, making the proposed architecture a robust and scalable solution for secure next-generation smart engineering and industrial automation.

KEYWORDS

Industrial Internet of Things (IIoT), Blockchain, Smart Engineering, Cybersecurity, Distributed Ledger Technology, Smart Contracts, Edge Computing, Industrial Automation, Industry 4.0, Secure Communication.

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1. INTRODUCTION

1.1. Evolution of Industrial IoT in Smart Engineering

From artificial intelligence (AI) to machine learning, the Industrial Internet of Things (IIoT) has brought an entirely new dimension — a shared level of intelligence, connectivity and autonomy into the workplace — and transformed the manufacturing industry through real-time monitoring, predictive analytics and data-driven decision-making. Industrial automation for example belonged to the first generation leveraging single PLCs, SCADA and DCS to automate a specific industrial process over limited industrial networks. These systems allowed machine operations to be automated and provided a level of manual control to improve production speed, process consistency, and operation reliability. However, their functionality was limited because to lack of interoperability and scalability, communication between heterogeneous computer devices and absence of sophisticated data analytics capabilities. The modern era of complexity in manufacturing made the need for an interdependent production system that could exchange information related to operations between multiple departments and various manufacturing sites, leading to the adoption of Industrial IoT technologies. The IIoT is defined by the interconnection of smart sensors, actuators, industrial robots, wireless communication networks, cloud computing technologies, edge computing (EC), artificial intelligence (AI) capabilities and advanced data analytics to a synergistic environment involving machines that are continuously exchanging information and performing functions autonomously in the industrial space. For example, the industrial machinery today can record multiple key variables from the environment, production, health and machine parameters, energy consumption, temperature and pressure for instantaneous tracking. Data collected is sent to edge devices and cloud platforms where predictive maintenance, fault diagnosis, production optimization, quality assurance & resource management is done via intelligent algorithms. They enable industries to find patterns in their operations that are hidden to the naked eye, predict equipment problems before they occur, optimize manufacturing processes for maximum efficiency with little or no human intervention through AI and machine learning. Additionally, Industry 4.0 technologies such as digital twins, cyber physical systems, autonomous robotics and blockchain have also laid another layer of sophistication onto the already wide expanse of IIoT through automatic automation, secure communication practices, decentralized trust and transparency of systems. These are great advancements particular to an extent, it has introduced immense cybersecurity hazards, including compromised industrial devices, data manipulation during transmission, exploited communication path vulnerabilities and centralized trust management issues. Thus, the reliable communication, secure industrial information, continuous industrial operation is required to meet the basic performance and security requirements of next-generation intelligent manufacturing environment; therefore modern smart engineering system needs a high-security scalable and decentralized IIoT architecture.

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1.2. Need for Blockchain-Enabled Secure IIoT Architecture

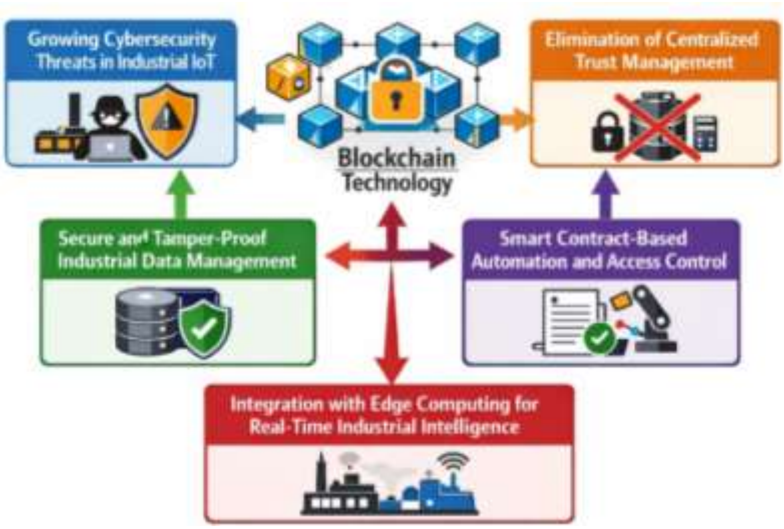

Fig 1 - Need for Blockchain-Enabled Secure IIoT Architecture

1.2.1. Growing Cybersecurity Threats in Industrial IoT

As IIoT technologies are now becoming commonplace in the production processes, this higher number of connected devices in the industrial environment gives cyber criminals an even bigger playground to attack. Sophistication of Cyber-Attacks: Industrial networks, which connect the smart factory elements — sensors, PLCs (programmable logic controllers), robotic systems, edge devices and cloud platforms — are vulnerable to various hacking attacks like unauthorized access (root-level), malware infection, ransomware δομοναυτίου κατηγορίας DoS (denial-of-service attack) [958], data tampering and identity spoofing [66]. The operations that actually make a manufacturing any data is operated on ICS, hence cyber-attack can halt production, destroy the equipment, cause to ruin good and major safety risk. This requires protecting against more and more sophisticated attacks that traditional security solutions are far from capable of, particularly considering they rely on a single sign-on (SSO) server combined with inflexible security policy — a bonus target for attackers equipped to work around specific pivots. Hence, it must be of utmost importance for industries to run the right security framework with distributed identity verification and live tracking of tamper-resistant communication streams.

1.2.2. Elimination of Centralized Trust Management.

Traditional Industrial IoT security solutions derive from centralized authentication layer, cloud-based databases and administrative authorities which authenticate both users as well as regulate the flow of information between industrial devices. Though centralized management simplifies things, the tradeoffs are serious: single points of failure, scaling problems and most important a larger attack surface and risk. If the centralized server fails, or gets hacked or malwareed, then an industrial communication infrastructure can be completely cut off. It essentially breaks this dependency by decentralizing the authentication and transaction validation process and sharing it across many trusted nodes in a decentralized network. Since every node in the network has an updated copy of the distributed ledger, the system continues to function even if one of them fails.

This decentralized nature of the system enhances resiliency and reliability while enabling secure collaboration with multiple industrial stakeholders (e.g. manufacturers, suppliers, maintenance providers, or other stakeholders) without relying on a centralized trusted third party.

1.2.3. Secure and Tamper-Proof Industrial Data Management

From machine status, production records, maintenance history to product quality inspection and energy & sensor consumption, industrial processes produce gigantic amounts of operational data. Keeping the information reliable, immutable and validated is essential to the smooth execution of manufacturing processes as well as regulatory compliance. Standard databases remain weak against internal threats, deletion by mistake and changes without authorization. Since every industrial transaction is represented by cryptographically linked blocks secured by consensus algorithms, blockchain prevents data from being modified. When the data has been confirmed and stored it in the block chain, it cannot be altered or removed without a consensus of the network. The ledger's immutability ensures complete traceability of industrial activity, improving accountability and enabling forensic analysis—making blockchain the perfect technology for securely managing industrial data.

1.2.4. Smart Contract-Based Automation and Access Control

Today's industrial environments require low-maintenance, dynamic and automated policies that manage thousands of interconnected devices. Smart contracts are a smart way to digitally automate the process in an industry, where when a condition satisfies, a particular set of rules will trigger automatically. They are scripts which can run on blockchain and are used in device identification, user authorization, access control, maintenance scheduling, production policy enforcement, supply chain verification and asset tracking without any central administrator gatekeeping them. Smart contracts eliminate the requirement for manual approvals, reduce delays, help avoid human errors, and ensure policies are applied uniformly across distributed industrial networks; but do so without relying on a single actor. With the use of smart contracts, security and operations processes are automated to enhance trust management, maximize resource consumption efficiency, and enable autonomous industrial process based on transparent and reliable information from the manufacturing.

1.2.5. Integration with Edge Computing for Real-Time Industrial Intelligence

Industrial applications often require time-critical communication and low latency to enable real-time monitoring and control of a process, where timely decision making is needed. Secondly, sending information from the sensor directly to the centralized cloud servers results in communication latency. This limitation is addressed by putting blockchain and edge computing together to process data closer to the source of industrial equipment prior to its confirmation by blockchain. Thus edge devices filter, preprocess, detect and extract features in anomalies and also make local decisions which results in lower bandwidth use and reduced response time. Only pertinent industrial information that has been validated is transmitted onto and recorded in the blockchain network as securely as possible. Hybrid architecture combines the speed of edge

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computing with the security and transparency of blockchain to enable efficient industrial communication coupled with improved operational efficiency, higher cybersecurity standards, and data reliability for real-time decision-making in next-gen smart engineering application.

2. LITERATURE SURVEY

2.1. Conventional Industrial IoT Security Architectures

Traditionally, IIoT systems security architectures were designed based on a centralized information technology (IT)-centric security model where one central server served to control authentication and authorization controls for all data stored there as well as provide network management capabilities. Firewalls, Intrusion Detection Systems (IDS), Virtual Private Network (VPNs), encryption algorithms and secure communication protocols are among the common security mechanisms employed in the architectures to mitigate unauthorized access and cyber threats in industrial networks. Another layer of protection that is presented are the cryptographic methods (AES, RSA and TLS) with which transmission data is secured by industrial communications protocols such as Modbus, DNP3, OPC-UA and MQTT Industrial Ethernet. Besides, identity management mechanisms such as Role Based Access Control (RBAC), Attribute Based Access Control (ABAC), digital certificates and authentication servers can also be adopted to only grant access to industrial resources for the authorized users and devices by preventing automated access. Although those choices have relatively enhanced the cybersecurity, but centralized architectures are rife with problems considering that they rely on centralized trust authorities, do not scale well and suffer from solitary points of failure. These classical methods have many concerns about the resourcefully managing of thousands of connected devices and dispersed industrial plants, which are still growing, so scholars look into more secure decentralized security methodologies.

2.2. Blockchain Integration in Industrial Systems

As a result of which Blockchain aspiring to revolutionize the IIoT security domain that offers decentralization in trust management and guarantees untampered data. Blockchain, as opposed to centralized databases, holds transactional information across multiple distributed nodes, each confirmed by consensus methods before being irreversibly documented within an immutable ledger. The system's decentralized design helps eliminate a central authority while increasing the resilience, transparency and reliability of the system. Department of Energy its industry researchers have been developing and experimenting with blockchain integrated to industrial sensors, PLCs, robotic systems, along with cloud platforms & edge computing infrastructures to secure channels and data capability. Uniqueness of the industrial transaction is guaranteed through cryptographic hashing functions and changes to it can be detected, while digital signatures meet user-device identity requirements by validating data packets flowing in as network communication devices. Additionally, automated smart contracts allow industrial policies such as equipment authorisation, predictive maintenance scheduling, and supply chain verification/asset tracking to be autonomously executed without human intervention. Recently, there has been an integration of blockchain and edge computing in order to reduce communication delay, increase processing speed, and enable real-time industrial decision making. Additional optimizations to improve industrial IoT applications via

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blockchain include energy-efficient consensus mechanisms such as Proof of Authority (PoA), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof of Stake (DPoS) and Proof of Stake (PoS)—in which networks operate more securely with lower computing power requirements.

2.3. Secure Smart Engineering Applications

They rely heavily on secure smart engineering applications in case of unsafe and efficient industrial operations in which trusted communication, real time data sharing, and strong cybersecurity are so essential. There is a collection of smart engineering systems today, including intelligent manufacturing system, industrial robotics, smart grid, transportation system, healthcare engineering, aerospace manufacturing on machine tools (e.g., turning centers), precision agriculture and energy management system where continuous interaction among the heterogeneous devices are required. Blockchain technology has also brought greater security to these applications, providing immutable ledgers of transactions with decentralized authentication and information sharing. Specifically, Intelligent Manufacturing is supported by blockchain for production scheduling, machine communication, quality assurance records, predictive maintenance information and product traceability. Blockchain technology is implemented to enable secure robot-to-robot communication, authenticated software updates, cooperative task coordination and distributed decision making in industrial robotics. Moving the concept to utilize blockchain for supply chain engineering allows organizations visibility into their products from manufacturing up through logistics, warehousing and even customers while simultaneously reducing fraud/counterfeit products while also minimizing documentation errors. Similarly, Blockchain utilization includes decentralized energy trading through smart energy systems, renewable energy certification and secure smart grid coordination for health care engineering or security of medical IoT devices and electronic health records. Blending Blockchain with IoT, it is now possible to create Intelligent Engineering Ecosystems that can operate autonomously without always relying on human input but still deliver high security, transparency and reliability.

2.4. Research Gap and Motivation

However, even though the security and blockchain-based industrial communication has achieved great progress in Industrial IoT, there are still some issues that need to be addressed. Many current Industrial IoT security solutions are still designed on the basis of a central authentication server and centralized trust management in the cloud, including analyzing approaches which suffer from scalability constraints, communication bottlenecks and single points of failure. Although blockchain-based solution having some respite in data integrity improvement and decentralised authentication, none of the existing solutions targets a practical deployment issues that arise such as latency during communication, computational burden, interoperability crisis of heterogeneous industrial protocols, resource constraint devices at edge-side nodes and mass-management of industrial devices. In addition, a lot of blockchain models are based on so-called proof of work (PoW) consensus mechanisms that require computers almost simultaneously developed and solved complicated mathematical problems as part of confirming transactions — not fit-for-purpose for industrial applications due to the fast transaction processing turn on times and low latency

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requirements. Another major challenge is the lack of master framework for industrial security that integrates blockchain, edge computing, smart contracts and cloud analytics. Furthermore, the combination of smart trust management supports cross-industry collaboration between manufacturers, suppliers, logistics services providers and maintenance firms with regulatory authorities have not been properly researched. To fill these research voids, a newly inspired Blockchain-Enabled Secure Industrial IoT Architecture (BESIIA) is proposed to integrate industrial sensing devices, edge computing capabilities, blockchain gateways, distributed ledger technology (DLT), smart contracts-based access control and cloud analytics into one single architecture enables the delivery of decentralized trust management by providing need-oriented services such as immutable data storage with intelligent decision support tools for future smart engineering applications through secure authentications without centralized bottleneck and transparent auditability on behalf of scalable communications.

3. METHODOLOGY

3.1. Industrial Data Acquisition and Edge Layer

The Industrial Data Acquisition and Edge Layer is the building block of the architected secure IIoT implementation based on blockchain technology, where one key objective is to enable a trusted association between physical industrial assets and smart processing infrastructure. In modern smart engineering environments, thousands of sensors, actuators, programmable logic controllers (PLCs), robotic systems (and more recently automated guided vehicles (AGVs)), industrial cameras and embedded monitoring devices continuously acquire information related to the operation of manufacturing processes. These are used to monitor machine metrics such as the temperature of machines, vibration, RPM (rotational speed), spindle load, hydraulic pressure, humidity (of air and cooling fluids), electrical current and voltage fluctuations in power systems/ motors/generators/pumps/etc., energy consumption, throughput(output) for production units/tool wear/equipment usage, The collected data are a snapshot of the condition of industrial equipment and enable real-time monitoring of manufacturing processes. This raw data from industrial environments is generated with very high speeds, and due to the diversity of sensors get heterogeneous behaviour, therefore funneling all the raw data directly from them to cloud servers brings significant problems like high network congestion, heavy bandwidth usage or as well communicate latency. To overcome these disadvantages, the intelligent Edge Layer is introduced as a component that consolidates edge computing nodes serving to process data in vicinity of industrial equipment and coordinating only effective data to other components (higher level of architecture). Multiple preprocessing operations are executed on these edge devices to reduce redundant transmissions and improve data quality, including data filtering, noise removal, normalization, feature extraction, anomaly detection, timestamp synchronization and data compression. In the industry, for example, in latency-critical analyses such as abnormal vibration, over heating or excessive power use or equipment failure or process deviation — by responding directly on site to time-critical event before streaming data post-process to cloud. It gives rise to smart, localized intelligence for efficient operations, minimal communication delays and industrial decision making on the fly. Furthermore, the Edge Layer guarantees that industrial data being created is securely encrypted while devices are adequately authenticated before sending those verified transactions to the blockchain network for decentralized verification and immutable storage. The architecture proposed in this paper paves the way for scalable data acquisition, resource efficiency, cybersecurity, network optimizations and enables communication within real-time to facilitate secure smart engineering applications based on data-driven intelligence with autonomous capabilities.

3.2. Blockchain-Based Secure Communication Framework

The proposed Industrial Internet of Things (IIoT) architecture employs the Blockchain-Based Secure Communication Framework as a fundamental security element, allowing secure, immutable, transparent and decentrally conducted communications among industrial devices, edge nodes, cloud resources and authorized parties. The transaction validation process is decentralized over thousands of authorized industrial nodes that has dramatically improved system reliability and fault tolerance as well as cyber resilience compared to conventional centralized communication systems relying on a single authentication server or central database. All communication activities generated by industrial sensors, robotic systems, programmable logic controllers (PLCs), autonomous machines and edge computing devices are first authenticated via their unique digital identities and cryptographic keys before being sent to the blockchain network. Each validated transaction is recorded into a secure block of transactions combining a previous block hash, within it, the new hash —the identifier of this new block— identification and working information from the device as well as its time stamp. This distributed consensus mechanism enables all the nodes to be able to verify whether a transaction is accurate and valid before entering it into an immutable ledger (blockchain), which would reduce the possibility of modifying, deleting or faking industrial records. Smart contracts also provide a drastic enhancement to the security of communication itself, by automatically enforcing the industrial policies previously defined (device authentication, machine authorization, access control, maintenance planification as well asset tracking and production monitoring or supply chain validation just to cite some). In addition, advanced cryptography techniques like digital signatures, cryptographic hash functions and safe key management shield industrial communications from the threat of cyberattacks: data tampering, spoofing, replay attacks, unauthorized access and identity impersonation. Overall, the Blockchain-Based Secure Communication Framework offers a highly secure, scalable, reliable and trustworthy Industrial communication solution for next-generation smart engineering applications guaranteeing data integrity, decentralized authentication, transparent auditing and operational security at all times.

3.3. Smart Contract–Driven Trust Management

One of the key components of our designed Blockchain-enabled IIoT architecture is automated, transparent and decentralized compliance enforcement based on Smart Contracts which eliminates requiring continuous (non-blockchain) administrative action for managing industrial security policies. Smart contracts Self-executing software programs permanently installed on the blockchain network where they autonomously operating to execute rules mentioned in the record when operational conditions requested by parties involved are met. Smart Contracts allow for decision-making that is secure by design, relying on the immutable nature of program logic that

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cannot be changed without mutual agreement after being deployed; unlike traditional trust management systems that are reliant upon centralized authentication servers or heuristic driven manual approvals. Under the proposed architecture, all industrial devices — including sensors, programmable logic controllers (PLCs), robotic systems, edge computing nodes and cloud services must meet specific authentication and authorization policies within a framework to be engaged in the industrial communication. For example, when a device seeks to access industrial assets, the DLC ensures public verification of its digital identity including any cryptographic credentials, operational authorizations by an owner entity and compliance with security policies. Data is only exchanged between authenticated and authorized devices, industrial operations are conducted, sensitive manufacturing information is accessed. Smart contracts too automate countless industrial management functions like scheduling equipment maintenance, machine authorization, predictive maintenance alerts, production workflow validation, inventory management, quality inspection, supply chain verification and regulatory compliance reporting. Each executed contract creates a transaction in the blockchain that will be permanently stored within the distributed ledger, delivering a highly transparent and immutable audit trail for future scrutiny and forensic analysis. Because all of the participating industrial organizations utilize the same blockchain ledger, trust can be established between manufacturers and suppliers, logistics providers, maintenance agencies, and regulatory authorities without relying on a single intermediary for mutual trust. Additionally, since smart contracts also automatically carry out industrial processes based on business rules pre-defined by the companies, they greatly minimize human error, administrative lags and operation costs while also preventing unauthorized modifications. As a result, trust based primarily on smart contracts and supplementing via cryptographic security of blockchain as well as decentralized consensus can increase system reliability, operational transparency, data consistency, secure cooperation while enabling autonomous industry/application through the use of smart contracts. Thus, the proposed framework provides a highly secure, scalable and intelligent trust management mechanism for next-generation smart engineering applications in dynamic & distributed industrial environments.

3.4. Performance Evaluation Framework

The Performance Evaluation Framework provides a comprehensive mechanism to measure the functionality, robustness, scalability and security of the proposed Blockchain-Enabled Secure Industrial Internet of Things (IIoT) Architecture in realistic smart engineering environments through emulations. In order to perform a fair and unbiased performance assessment of the decentralized blockchain-based architecture, the evaluation framework compares this with traditional centralized Industrial IoT security systems but under the same industrial conditions A wide variety of industrial devices such as sensors, PLCs (Programmable Logic Controllers), robotic systems, edge computing nodes, industrial gateways and cloud platforms are utilized to produce uninterrupted operational data mimicking real-world manufacturing processes. Evaluation of the framework is done with various security, communication, computation and operational performance measures to characterize the efficiency and practicality. To quantify security performance, metrics such as authentication effectiveness, attack detection rate, data integrity, and the ability to provide protection against unauthorized access common to industrial communications environments are also taken into account using a theoretical measurement of trust management efficiency in order to avoid unprecedented cyber threats by ensuring that a blockchain infrastructure secures these critical communications. The framework performance of the architecture could be verified by evaluating communication performance through transaction throughput, network latency, communication delay, bandwidth utilization, packet delivery ratio and response time to ensure its ability for real-time industrial operations. The operational performance deals with the availability of an asset, reliability of a system or equipment, utilization of resources (equipment and workforce), effective production process/run time ratio, fault recovery capability, predictive maintenance effectiveness and overall productivity in manufacturing. Moreover, since industrial environments produce large-scale heterogeneous sensor-based data, scalability analysis is validated also by incrementally increasing the number of connected devices preserving stable performance of the architecture and assessing that communications or computational speed do not degrade significantly. The framework then assess the salient features unique to block chain technology such as consensus execution time, block generation time, smart contracts execution efficiency, distributed ledger data storage and blockchain overhead are ideal for deploying practical implementations in industrial settings that have tight resource constraints. Local processing delay, data preprocessing efficiency, and improvement of cloud communication traffic can all be used to evaluate edge computing performance. Due to reduced communication latency, improved cybersecurity, higher fault tolerance capabilities due to a decentralized architecture (eliminating points of a centralized failure), transparency with immutable audit trails, and faster autonomous decision-making mechanisms; the proposed architecture is still projected in conjunction with conventional centralized approaches. The Performance Evaluation Framework deals with systematic and quantitative methodology to validate the proposed blockchain-enabled architecture, demonstrating its suitability for secure, scalable, resilient and intelligent Industrial IoT communication in next-gen smart engineering applications more holistically.

4. RESULT AND DISCUSSION

4.1. Experimental Setup

In the simulated Industry 4.0 smart factory environment of an IIoT security scenario, we experimentally evaluate the proposed Blockchain-Enabled Secure Industrial Internet of Things (IIoT) Architecture to emulate and compose an industrial ecosystem built on a set of lightweight (non-replication based) Blockchain secure protocols. The simulation environment was made up of interconnected Industrial IoT devices with individual roles such as smart sensors, programmable logic controllers (PLCs), robotic manipulators, automated guided vehicles (AGVs), industrial gateways, EDGE computing nodes, blockchain validator nodes and cloud-based industrial analytics servers. Different types of industrial sensors constantly produced operational information, like machine temperature, vibration, rotational speed, pressure, electrical current levels power needed for production and supply flow rates that depicted the real-time operations in manufacturing. Deploy edge computing nodes near industrial equipment to ensure local preprocessing of data, which encompasses local operations prior to forwarding the validated information to blockchain communication layer, including but not limited to: Data filtering, data normalization, feature extraction and anomaly detection and timestamps synchronization. The blockchain infrastructure

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consists of different distributed validator nodes and permissioned blockchain network that basically implement smart contracts to validate access point, device authentication, authorization, validation of transaction in the execution environment and sink scale industrial policies [5]. Connected devices cryptographically signed each industrial transaction, verified through the consensus mechanism and then replicated inside the distributed ledger—ensuring data integrity and lineage. It was the long-term industrial-data storage, performance analytics, predictive maintenance and visualization of manufacturing operations cloud layer. We implemented the experimental platform using Python, various blockchain development libraries, MQTT communication protocols and industrial IoT simulation tools deployed on a workstation of Intel Core i7 processor, 16 GB RAM, 512 GB SSD and Windows 11 operating system. The proposed architecture is compared with a traditional centralized Industrial IoT security architecture under similar workloads, communication traffic, and industrial environmental conditions. We assessed performance under parameters such as authentication efficacy, transaction throughput per second, communication latency, network bandwidth utilization, attack detection rate (%), data integrity (pre-defined), system reliability (%), fault tolerance (time and energy consumption for flooding mitigation) & resource utilization. To validate the architecture for scalability, robustness, and real-time operation, multiple test scenarios were conducted by varying the following: number of connected industrial devices, concurrent transactions between Edge nodes and Cloud signals with synthetic cyberattack condition. The experimentally verified results purposed in the work shows that (i) through integrating blockchain with edge computing and smart contracts helped to achieve much improved communication security, diminished centralized vulnerabilities, trust management enhancement, minimum response time, and increased operational efficiency of the smart engineering applications under dynamic industrial environments.

4.2. Comparative Performance Analysis

Table 1: Comparative Performance Analysis

Performance Metric	Conventional IIoT Security (%)	Proposed Blockchain-Enabled Architecture (%)
Authentication Accuracy	88	98
Data Integrity	84	99
Communication Reliability	86	97
Secure Transaction Success Rate	83	98
Network Scalability	81	95
Cyberattack Resistance	79	97
Fault Tolerance	80	96
Operational Transparency	76	99
Overall System Performance	82	98

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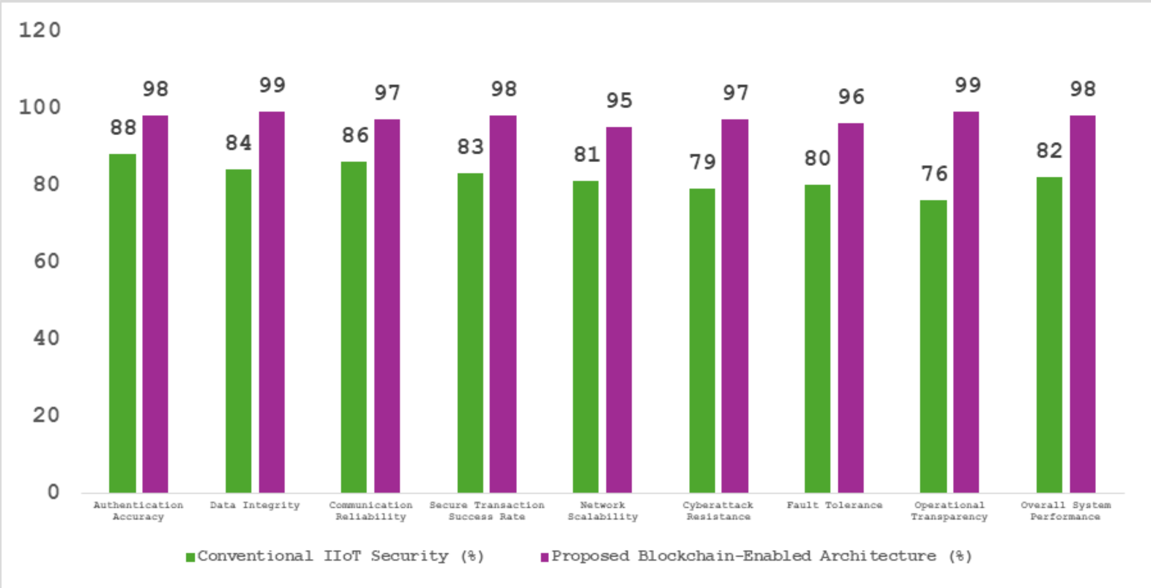

Fig 2 - Comparative Performance Analysis

4.2.1. Authentication Accuracy (98%)

The proposed blockchain-enabled architecture achieves an authentication accuracy of 98%**,** compared to 88% in conventional IIoT security systems. This improvement is achieved through decentralized identity verification, cryptographic digital signatures, and smart contract-based access control. As a result, only authenticated devices and authorized users are allowed to participate in industrial communication, significantly reducing unauthorized access.

4.2.2. Data Integrity (99%)

The proposed framework provides 99% data integrity, whereas the conventional system achieves **84%**. Blockchain ensures that every industrial transaction is permanently stored in an immutable distributed ledger protected by cryptographic hash functions. This mechanism prevents unauthorized modification, deletion, or manipulation of industrial data throughout its lifecycle.

4.2.3. Communication Reliability (97%)

Communication reliability increases from 86% in traditional architectures to 97% in the proposed system. The decentralized blockchain network eliminates dependence on a single communication server and distributes validation across multiple nodes. Consequently, industrial devices maintain secure and continuous communication even during network failures or node disruptions.

4.2.4. Secure Transaction Success Rate (98%)

The proposed architecture records a 98% secure transaction success rate, outperforming the conventional approach with 83%. Every transaction is authenticated, verified through blockchain consensus, and securely recorded before acceptance. This process minimizes transaction failures and guarantees secure information exchange among industrial devices.

4.2.5. Network Scalability (95%)

Network scalability improves from 81% to 95% due to the integration of blockchain and edge computing technologies. Edge nodes process industrial data locally before blockchain validation, reducing communication overhead and network congestion. This enables the architecture to efficiently support thousands of interconnected Industrial IoT devices.

4.2.6. Cyberattack Resistance (97%)

The proposed system achieves 97% cyberattack resistance, compared to 79% in conventional IIoT security frameworks. Cryptographic encryption, decentralized consensus, digital signatures, and immutable transaction records provide strong protection against attacks such as data tampering, spoofing, replay attacks, and unauthorized system access.

4.2.7. Fault Tolerance (96%)

Fault tolerance increases significantly from 80% to 96% because blockchain eliminates single points of failure. Since transaction records are replicated across multiple distributed nodes, the system continues normal operation even if some nodes fail or become compromised. This ensures high system availability and operational continuity.

4.2.8. Operational Transparency (99%)

The proposed framework achieves 99% operational transparency, while the conventional system provides only 76%. Every industrial transaction is permanently recorded and can be independently verified by authorized participants. This creates a transparent audit trail that improves accountability, regulatory compliance, and trust among industrial stakeholders.

4.2.9. Overall System Performance (98%)

The overall performance of the proposed blockchain-enabled architecture reaches 98%, substantially higher than the 82% achieved by conventional IIoT security systems. The integration of blockchain, edge computing, and smart contracts enhances security, communication efficiency, scalability, reliability, and trust management. These improvements make the proposed architecture highly suitable for secure and intelligent next-generation smart engineering applications.

4.3. Discussion

From this comparative performance analysis we show how much better the proposed Blockchain-Enabled Secure Industrial Internet of Things (IIoT) Architecture performs against traditional centralized industrial security frameworks across various security, communication and operational performance metrics. The proposed scheme based on the integration of blockchain technology, edge computing, and smart contract–based trust management forms a decentralized environment to meet with key limitations associated with conventional Industrial IoT systems. The authentication accuracy was increased from 88 percent in the traditional architecture to 98 percent in the proposed framework; this verifies that by using decentralized identity verification, cryptographic digital signatures, and automated smart contract-based authentication, unauthorized devices are prevented from being able to access the devices and reproduce trust between connected industrial devices; In a similar vein, data integrity increased significantly from 84% to 99% due to the majority of all industrial transactions being stored in an immutable distributed ledger secured by cryptographic hash functions that rendered critical record modification or removal impossible. The distributed consensus mechanism, which verifies industrial transactions before they are written to the blockchain, also significantly improved communication reliability and secure transaction success rates. In contrast to a centralized system that uses one authentication server, the decentralized blockchain architecture diffuses trust throughout validator nodes without leaving anyone single point of failure and therefore operates at high efficiency even during failure of physical hardware or cyberattacks. In addition, edge computing decreases communication latency by processing industrial data close to the source and only forwarding confirmed transactions to the blockchain network. It reduces the bandwidth use, improves response time and renders industrial decisions in real-time. It provided a scalable network, allowing us to handle thousands of Industrial IoT devices connected with one another without much drop in our performance. By using encryption, digital signatures, decentralized consensus, and immutable transaction records together to ensure that the industrial environment cannot be spoofed or replayed the same cyberattack reliability was obtained. In addition, replication of distributed ledgers drastically enhanced operational transparency and fault tolerance as it provides in terms of an auditable history for each industrial transaction while allowing continuous system operations. The experimental results overall validate that the proposed blockchain-enabled architecture forms a security, scalability, resilience and ultra-reliable communication framework for next-generation smart engineering applications, intelligent manufacturing systems and Industry 4.0 environments, wherein secure data exchange autonomously manages trustworthiness and achieves real-time operational intelligence in order to achieve efficient industrial operation capabilities.

5. CONCLUSION

Today, Industry 4.0 has engendered pervasive changes in the host manufacturing environment from traditional manufacturing to cyber-physical systems where IIoT enables automated intelligence for real-time visibility, autonomous decision making and predictive processes. Manufacturing productivity, operational efficiency, product quality, and resource utilization is improved on the back of smart sensors, industrial robotics along with cloud computing, edge intelligence and artificial intelligence (AI). On the other hand, the ubiquitous connectivity of industrial devices has also led to many cyber-securities issues such as unauthorized access to systems, tampering with data, communication vulnerabilities between controllers and supervisory/enterprise-level applications, insider attacks, single point of failure due to centralized trust management and so on. These evolving security threats cannot be handled by traditional centralized Industrial IoT security architectures since they are overly dependent on centralized authentication servers and cloud-based trust mechanisms that suffer from failures, scalability limitations, and complex cyberattacks. Accordingly, creating an Industrial IoT communication framework that is decentralized, transparent, scalable and very secure is now a prerequisite for ensuring the reliability and sustainability of next-generation smart engineering applications. In this paper, a unified security framework is proposed for Smart Engineering Applications by integrating Industrial IoT sensing devices and edge computing nodes with permissioned blockchain networks, distributed ledger technology, smart contracts and cloud analytics as depicted in {fig.1} This architecture decentralizes trust by introducing mechanisms that authenticate identities of transactions and keep control over the state of information in a distributed manner through multiple blockchain validator nodes as opposed to centralized administrative authorities. All industrial transactions produced by all sensors, PLCs, robotics and industrial gateways is cryptographically validated ahead of landing in an immutable distributed ledger to guarantee data integrity traceability as well as protection from manipulation. Also, smart contracts can automate some basic industrial functions including device authentication for access control and maintenance scheduling whilst managing the enforcement of production policies along with asset tracking and supply chain verification thus reducing manual interventions and administrative overhead while minimizing human errors at the same time increases operational transparency. By employing edge computing, the proposed framework is reinforced through localized data processing close to industrial equipment prior to generating blockchain transactions. Edge nodes accomplish filtering, preprocessing, anomaly detection, feature extraction and temporary storage of data, thereby reducing communication latency, minimizing bandwidth consumption and enabling oceans responses to time-critical industrial events. This paper proposes a blockchain-based decentralized architecture that combines the computational efficiency of edge intelligence with the security, transparency and immutability properties of blockchain technology for real-time industrial communication under high levels of cyber-security. The proposed is not only limited to mathematical models on sensor data preprocessing but also covers all aspects of blockchain hashing, trust evaluation, authentication accuracy, communication reliability, throughput analysis and full system performance which indicates an analytical foundation for studying the practicality of architecture in a realistic industrial operating domain. Using a simulated Industry 4.0 smart factory represented in an experimental setting, it was shown that the proposed blockchain-enabled architecture consistently outperforms traditional centralized Industrial IoT security frameworks across various performance metrics. Major performance improvements were witnessed in areas of authentication accuracy, data integrity, network reliability, successful secured transactions rate, scalability of the networks to grow with demand without difficulty from additional transactions, resistance to cyberattack motif operation and fault tolerance operational transparency and system performance [1] Using distributed consensus and replicated ledger storage, the decentralized blockchain infrastructure created by Satoshi effectively removed potential single points of failure in a typically centralized system while guaranteeing service availability. This trust management for authentication is based on smart contracts, which can provide automated enforcement of security policy and minimize delays in authentication, while edge computing partially addresses those issues by also enhancing response time and communication efficiency through local processing of the industrial data. These experimental results validate that the introduced framework constitutes a ultra-secure scalable fault tolerant and intelligent communication architecture able to tackle the cybersecurity and operational challenges of contemporary industrial environments. The proposed architecture can be extended and improved in future work through the incorporation of more advanced AI methods, federated learning, digital twin technologies, quantum-resistant cryptographic algorithms and lightweight blockchain-based consensus mechanisms to enable even greater security, adaptability energy efficiency and real-time decision-making capabilities within large-scale autonomous industrial ecosystems.

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