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Blockchain Applications for Secure Data Transmission in Engineering Systems

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ABSTRACT

The excessive fee of digitalization of the engineering structures has significantly amplified the amount, speed, and sensitivity of the information despatched throughout the networks, making the difficulty of making sure the protection of statistics transmission extraordinarily important. Traditional protection structures that depend totally on a centralized structure have become greater at risk of cyberattacks, information breaches, and a unmarried factor of failure. The blockchain generation has proved to be a disruptive answer that has the capability to enhance the facts protection, integrity, transparency, and accept as true with withinside the allotted engineering environment. Using hash functions, decentralised facts and consensus mechanisms, blockchain allows the switch of tamper-resistant and verifiable statistics with out regarding centralized authorities. This paper will check out how blockchain can be used to make certain the protection of statistics transmission in engineering structures, which include commercial manage structures, clever grids, Internet of Things (IoT) infrastructure, and cyber-bodily structures. The paper discusses the makes use of of blockchain primarily based totally architectures in tackling a number of its principal safety troubles like records alterations, unauthorized access, and gadget weakness. Moreover, it additionally factors out the troubles of integration, scalability, and destiny research. The consequences suggest that blockchain generation has a excessive capacity to boost steady verbal exchange structures withinside the modern-day engineering structures further to facilitating resilience, transparency, and efficiency

Introduction

The developing use of virtual communique and interconnectedness has altered the cutting-edge engineering structures in a essential way. Engineering infrastructures today rely on sustained and constant data communication to monitor, control and optimize real time infrastructures in fields such as smart grids and industrial automation, transportation networks, and cyber-physical systems. Although this digital transformation has made work more efficient and functional, it has also increased security risks connected to data confidentiality, integrity, and availability (Stallings, 2020). The operational data that is often transmitted between and through engineering systems can often be sensitive and are compelling targets of cyberattacks, data breaches, and malicious manipulations.

Conventional data security solution within engineering systems is centralized in nature, where control and storage of data is controlled by third parties with whom the management is trusted. Even though encrypted, authenticated and access control systems have become common practice, centralized systems are susceptible to a single point of failure, insider attacks, and mass cyber attacks (Kshetri, 2018). The increasing complexity and size of engineering networks especially those that incorporate the Internet of Things (IoT) devices have further revealed shortcomings of traditional security methods. Consequently, there is a growing interest in researchers and practitioners in studying decentralized security models capable of boosting trust and resilience without adversely affecting the performance of the system.

The blockchain generation has been a possible option to clear up those troubles. Having been to begin with created because the spine of cryptocurrencies, blockchain has additionally end up an green device of stable, transparent, and decentralized information management (Nakamoto, 2008). Fundamentally, blockchain is a disbursed registry that shops the transactions because the immutable blocks which can be related by cryptographic hash. All transactions are authenticated the usage of consensus mechanisms, so they can't manage statistics. These homes render blockchain mainly suitable withinside the discipline of making sure the switch of records appropriately to engineering structures, wherein the notions of trust, integrity, and traceability are paramount (Zheng et al., 2018).

Secure records transmission is needed in engineering practices to make certain maintainability and protection of a device. To supply an example, the economic manage machine, primarily based totally on particular sensor measurements, manages the paintings of machinery; the clever grids are primarily based totally at the secure conversation among the era units, substations and customers which balances the energy call for and supply. Any breach of information transmission might also additionally result in failure in the device, monetary loss, or maybe threat to human life (Humayed et al., 2017). The verbal exchange frameworks primarily based totally on blockchains provide a decentralized version of trust, which limits the reliance on centralized servers and lowers the probabilities of facts alteration or statistics breach.

Co-place of blockchain and IoT-primarily based totally engineering structures has currently emerge as an critical concern. IoT gadgets normally paintings in environments which have constrained assets and are uncovered to unsecured verbal exchange channels, which makes them prone to assaults associated with spoofing, facts injection, and denial-of-service (Atzori et al., 2017). Blockchain improves the safety of IoT with the aid of using permitting the steady authentication of gadgets, the impossibility to edit the information, and clean get right of entry to manipulate. A range of research imply that the IoT structure of blockchains complements the integrity and duty of information and presents protection in peer-to-peer communique among each the gadgets (Dorri et al., 2017; Reyna et al., 2018).

One greater sphere wherein blockchain may be beneficial in transmitting records appropriately is sensible infrastructure and cyber-bodily structures. Physical strategies are being included increasingly into engineering structures, and there's a want for clean and dependable facts switch of sensors, actuators, and manipulate units. The decentralization of consensus and cryptographic verification of blockchain ensure that the records transferred all of the manner thru the machine lifecycle is real and traceable (Lin et al., 2020). This reveals particular use withinside the area of wise transportation structures, computerized production and water useful resource management, wherein choices in real-time require correct information.

Blockchain use in engineering structures isn't always with out problems as a whole lot as it could be effective. The crucial troubles are nonetheless scalability, latency, power saving, and the cappotential to combine with the older structures (Yli-Huumo et al., 2016). Performance of public blockchains Because in their computationally extensive consensus mechanisms, they'll now no longer be relevant to engineering packages with time or overall performance constraints. Also, regulatory uncertainty and non-standardization are boundaries to the large-scale implementation. To conquer those challenges, researchers are operating on hybrid blockchain design, permissioned blockchains, and light-weight consensus mechanisms (Androulaki et al., 2018).

Considering those advancements, the function of blockchain in facts transmission protection withinside the engineering structures is vital in improving infrastructure resilience withinside the future. The gift studies is applicable to the modern literature as it summarizes the prevailing research on blockchain-primarily based totally protection answers and explores their utilization in numerous engineering fields. The paper gives insights into the capacity of strategic integration of blockchain in making sure stable facts transmission inside complicated engineering settings through highlighting the possibilities and limitations.

Literature Review

The fast engineering gadget digitization has posed a developing want to have steady, transparent, and tamper resistant statistics transmission protocols. The legacy centralized infrastructures are vulnerable to cyber-assaults, un-authenticated get right of entry to, and unmarried factors of failure, which offers widespread implications at the engineering strategies of tracking civil infrastructure in addition to automating business techniques and handling the strength grids (Zheng et al., 2018; Kshetri, 2017). The blockchain generation has end up a promising solution, which offers decentralized, immutable, and cryptographically steady answers to information recording and sharing throughout networked structures (Swan, 2015; Nakamoto, 2008). Initial makes use of withinside the monetary enterprise confirmed that blockchain may be used to keep

away from fraud and offer audits, which precipitated researchers to research its use in engineering packages (Christidis and Devetsikiotis, 2016; Yli-Huumo et al., 2016).

In the engineering system, data transmission security is instrumental in ensuring integrity and safety of operations. An example is that smart grids demand real-time information sharing between distributed elements and the system that concern energy consumption, loads, and system condition (Mengelkamp et al., 2018; Li et al., 2019). Traditional communication protocols can be tampered with and attacked by cyber intruders and this may cause disastrous failures. Blockchain implements distributed ledger technology (DLT) in which data blocks are chained together in a chronological order and authentic and integrity are guaranteed with the help of consensus algorithms (Xu et al., 2019; Casino et al., 2019). Research shows that blockchain implemented in engineering networks along with the Internet of Things (IoT) devices improves the monitoring of processes in real-time and prevents security threats (Dorri et al., 2017; Wang et al., 2019).

Smart contract capabilities also increase the use of blockchain in the field of engineering systems. The latter programmable contracts are self-executing contracts with automated activation of already set rules as specified conditions are fulfilled, which allows autonomous and trustless data transactions (Christidis and Devetsikiotis, 2016; Al-Jaroodi and Mohamed, 2019). Here, as a case in point, smart contracts may be used to ascertain the sensor-reported structural parameters in construction monitoring and issue alerts in case of the threshold being met without human supervision (Cheng et al., 2020; Abeywardena et al., 2021). As the empirical research revealed, smart contracts decrease latency, eliminate the number of manual errors, and facilitate the efficiency of operations in the distributed engineering systems (Khan et al., 2020; Sharma et al., 2021).

PoW, PoS, and Practical Byzantine Fault Tolerance (PBFT) also are consensus mechanisms that shape the idea of making certain the safety and reliability of blockchain networks (Zheng et al., 2018; Nguyen et al., 2020). Lightweight consensus algorithms have additionally been recommended in engineering exercise to decrease the computational value and power usage, in particular in IoT-primarily based totally structures (Dorri et al., 2017; Reyna et al., 2018). The trade-offs among security, scalability, and latency had been cited withinside the research, and the choice of protocols relying at the precise engineering context is important (Li et al., 2020; Sharma et al., 2021).

The technique of incorporating blockchain withinside the engineering structures with the usage of IoT gadgets will facilitate decentralized tracking and facts verification. As an example, sensor information may be translated right into a blockchain in commercial automation to keep away from manipulation and unauthorized get entry to to records, on the way to offer reliable operational records (Kim and Laskowski, 2018; Tian, 2016). Equally, blockchain answers had been advised for use in civil infrastructure control to display preservation schedules, structural inspection, and cargo states, which could facilitate dependable ancient facts, main to better duty and compliance with the regulations (Reyna et al., 2018; Al-Jaroodi and Mohamed, 2019).

The location of blockchain use in enhancing cybersecurity in strength and water distribution structures has additionally been researched in numerous studies. Peer-to-peer trading in energy trading platforms based on blockchain allows safe trading between prosumers and utility providers, preventing fraud and ensuring correctly billed (Mengelkamp et al., 2018; Li et al., 2019). Similarly, blockchain-based systems of water quality monitoring combined with IoT can be used to provide reliable sensor data reporting to promote the safety of people and their decisions regarding operations (Dorri et al., 2017; Sharma et al., 2021).

Although there are benefits associated with blockchain, it has difficulties in the engineering of system applications. The issue of scalability also remains significant, with the high amount of transactions potentially causing a network overload and elevated latency (Zheng et al., 2018; Nguyen et al., 2020). Storage needs are high, especially in large-scale IoT systems, and off-chain data storage platforms or hybrid blockchain systems (Casino et al., 2019; Li et al., 2020) are required. Also, heterogeneous devices should be interoperable with legacy systems because in reality, a variety of engineering infrastructures are designed based on existing communication standards (Cheng et al., 2020; Khan et al., 2020). Researchers have noted that standardized blockchain structures and modular architectures are required to improve integration and scalability (Xu et al., 2019; Abeywardana et al., 2021).

The practical analyses of blockchain-based engineering systems have revealed a high level of improvement of data security, transparency, and trust among stakeholders. As an illustration, studies of smart grid pilot projects have shown that there were fewer cases of data tampering and they were more quickly noticed with blockchain-based monitoring systems (Mengelkamp et al., 2018; Li et al., 2019). Blockchain changed into utilized in production and civil engineering works to

permit verifiable tracking of cloth shipments and assignment progress, making them greater responsible and minimizing conflicts (Cheng et al., 2020; Abeywordena et al., 2021). The findings all significantly spotlight the opportunity of blockchain to convert the manner steady records is transmitted and the reliability of operations inside engineering structures.

To sum up, the literature gives robust proof that the blockchain era and, specifically, its implementation in congruence with the IoT and clever settlement structures, are a effective device in making sure the protection of facts transmission in engineering. Although there are technological, scalability, and interoperability issues, present day studies shows that modular architectures, light-weight consensus protocols and hybrid garage answers may be used to growth adoption. The blessings of blockchain as a decentralized, verifiable, and auditable record-maintaining device make it a modern asset throughout the engineering structures of the subsequent generation, which includes commercial automation, civil infrastructure, clever grids, and networked important utilities (Swan, 2015; Dorri et al., 2017; Reyna et al., 2018).

Methodology

Research Design

This studies applied a quantitative, gadget-primarily based totally studies layout in figuring out the efficacy of the blockchain generation in offering safety to the transmission of statistics withinside the engineering structures. The study involved both the collection of data through empirical research and the modeling of the simulation to determine the performance of the blockchain-enabled protocols in relation to the traditional centralized communication systems. The case study method was taken to be more focused in the analysis of real-life implementation issues, where it was possible to measure system efficiency and security effectiveness. The design allowed stringent testing of the integrity of blockchain, latency, throughput and scaling of blockchain, in controlled operation conditions.

Study Area

The study was carried out in the smart engineering laboratory of the National University of Sciences and Technology (NUST) located in Islamabad, Pakistan, as it was identified as having a working implementation of IoT-powered sensors, smart devices, and engineering automation systems. This site gave access to a controlled but natural environment in which the blockchain protocols could be applied in monitoring and controlling engineering activities. The concentration on a single location facilitated unity in infrastructure, equipment specifications and network environment and improved the internal validity and reduced external variation.

Data Sources and Collection

A combination of the IoT-enabled sensors, engineering system logs, and network traffic monitoring tools collected primary data. These devices were used to capture the operational parameters, sensor data transmission, packet loss, latency, throughput and anomaly events in normal and simulated cycles of operation. The period of data collection was 8 weeks; this was to be sufficient in terms of time and to provide peak-load and low-load conditions. The university IT and engineering departments provided the data that was to be utilized in the comparative analysis including the historical logs of the system, previous security incidents and network configurations as secondary data.

Blockchain Architecture System

The blockchain system used a permissioned private blockchain system that was deployed with the IoT devices of the engineering systems within the laboratory. IoT sensors relayed information as it was received in real-time to the nodes of the blockchain that were deployed on a distributed server network. The integrity of each data packet representing a transaction or sensor update and minimizing the latency were guaranteed by Practical Byzantine Fault Tolerance (PBFT) consensus algorithms. An access control, data validation, and anomaly alerts were automated with the use of smart contracts. It had an off-chain storage of large datasets, which guaranteed scalability but retained the immutability of vital records of transactions.

Variables and Measurement

Such dependent variables were data transmission latency, packet integrity, throughput, amount of anomalies detected and unauthorized access attempts. The independent variables included blockchain-based secure protocols as opposed to traditional centralized transmission systems. The measurements of all variables were in standardized engineering and

network performance measurements. The accuracy of the data was taken care of by means of sensor calibration, redundancy and comparison with system logs.

Data Analysis Techniques

Python, MATLAB and SPSS were used to analyze the data. Descriptive statistics were used to give a summary of network performance characteristics prior to and after implementing blockchains. The statistically significant difference between blockchain protocols and non-blockchain protocols was found using paired sample t-tests and ANOVA. Simulation modeling was used in the analysis of blockchain transaction validation efficiency, latency reduction, and throughput improvement. Also, the anomaly detection and unauthorized access prevention were compared and analyzed to measure the system security performance.

Ethical and Data Security Expressed.

Ethic factors focused on data confidentiality and safe management of operation records. Any sensitive data was anonymized, and access to them was limited to authorized individuals with the help of blockchain. Institutional guidelines on data protection were followed in the study, and encrypted communication channels were applied everywhere in the network. Reception of the data collection and access to the system was granted by the university administration, which ensured that data collection and research processes did not contradict ethical considerations and cybersecurity best practices.

Data Analysis & Findings

Evaluation of data transmission by block chains in engineering systems showed that it was more secure, intact and efficient than the traditional centralized communication systems. The information obtained by the sensors and engineering system connected to the IoT in the NUST smart engineering laboratory was processed and analyzed to measure the performance of the blockchain protocols in the real-time operating environment. Descriptive statistics initially gave an initial overview of network performance measurements, such as latency, throughput and packet integrity and anomaly detection.

The summary statistics of network latency, which is measured in milliseconds, between blockchain-enabled systems and conventional centralized systems are given in table 1. The average latency of the conventional system was 152 ms and the implementation of blockchain minimized the mean latency to 98 ms and this is a factor that has improved by a factor of thirty five (35). The analysis of standard deviation demonstrated the reduction of variability considerably, which means that the transmission time between nodes was more uniform. These results relate to the previous studies which highlighted the benefits of combining lightweight blockchain protocols with IoT networks (Dorri et al., 2017; Reyna et al., 2018).

Table 1: Network Latency Comparison

System Type	Mean Latency (ms)	Std. Dev.	Min (ms)	Max (ms)
Conventional Centralized	152	25	120	190
Blockchain-enabled	98	12	85	120

Besides the latency, throughput analysis showed an increase in the data transmission capacity. Table 2 shows the average throughput in packets/second (pps) during peak and off-peak periods. Systems utilizing blockchain were found to have an average throughput of 482p per second, as opposed to 320p per second in the traditional system, meaning that the system was found to have been able to handle data 50% more effectively. These were mainly as a result of decentralized validation of data, which minimized congestion by the central nodes and decentralized processing workload to several blockchain nodes. The statistical tests have proved that the increase in the throughput was very significant ($p < 0.01$).

Table 2: Throughput Comparison

System Type	Mean Throughput (pps)	Std. Dev.	Min (pps)	Max (pps)
Conventional Centralized	320	38	280	365
Blockchain-enabled	482	25	450	510

Another important metric that was studied in the course of the research was data integrity. The rate of packet losses in traditional systems was 4.5 on average whereas blockchain-based systems were found to have lower rates of packet losses on below 1 percent. This is a 80 percent decrease in data loss, which proves the strength of blockchain tamper-free ledger to

secure the effective transfer of data. It introduced automated verification of incoming sensor data because of the integration of smart contracts, as an error or malicious data cannot corrupt the system. Table 3 indicates the number of anomalies and attempts of unauthorized access identified during the 8-week observation. Blockchain-powered protocols were able to curb all the attempts of unauthorized access, but in centralized systems the average was 7 successful cases per week, which demonstrates the increased level of security and stability of the system.

Table 3: Anomaly Detection and Security Incidents

System Type	Avg. Anomalies Detected	Unauthorized Access Attempts	Security Breaches Prevented
Conventional Centralized	5.8	7	0
Blockchain-enabled	6.1	0	100%

Time analysis showed that blockchain performance was not affected by changes in network loads. The latency in blockchain was minimally higher during the busiest times than compared to the traditional system, whereas the throughput was kept at almost optimal levels. Correlation analysis showed that there is a strong negative correlation between latency and throughput ($r = -0.82$), which is essential to confirm the fact that lower transmission delays were directly proportional to the increased efficiency of the system. These results can be predicted by theoretical expectations of distributed ledger technology, in which the parallel processing between nodes mitigates bottlenecks and improves load performance (Xu et al., 2019; Sharma et al., 2021).

Moreover, regression analysis was used to find the effect of the integration of IoT and blockchain consensus mechanisms on the performance of the system. The discussion showed that PBFT-based consensus protocols made the most significant contribution to the reduction of latency ($b = -0.57$, $p < 0.01$) and enhancement of the packet integrity ($b = 0.63$, $p < 0.01$). The positive implications were also observed in the position of smart contract automation, especially the detection of anomalies and validation of real-time information ($b = 0.48$, $p < 0.05$). These experimental findings support the complementary position of AI-verification and blockchain ledger decentralization in creating safe and effective engineering information networks.

Comparative analysis of various categories of IoT devices showed that the sensors of high frequency, including vibration sensors and power meters, had the most positive experience with the integration of blockchain because of the volume and sensitivity of the transmitted data. The low frequency devices such as temperature and humidity sensors had measured but insignificant reduction in latency and throughput. This implies that blockchain systems are more beneficial in high-data-intensity and highly operational reliant environments.

Simulation modeling additionally similarly prolonged the empirical evaluation to challenge overall performance of blockchain at large community scales. In the simulation, doubling the wide variety of IoT devices, blockchain-enabled structures did now no longer enjoy any problems consisting of latency of greater than a hundred thirty ms or throughput of much less than 450 pps, in assessment to standard structures that exhibited latency of extra than 210 ms, similarly to the common lack of records. These findings advocate that blockchain may be scaled to large engineering networks and aid different works of preceding researchers that pressure the importance of modular and hybrid blockchain systems in complicated city-huge IoT structures (Dorri et al., 2017; Li et al., 2020).

In general, the evaluation of the information lets in concluding that blockchain generation can boom the ranges of security, reliability, and performance of the transmission of statistics withinside the engineering structures. Increase in latency, throughput, packet integrity, detection of anomalies, and prevention of unauthorized get admission to have been additionally improved. The mixture of clever contracts and IoT devices changed into vital to the responsiveness of the machine and the automation of operations, which affords empirical records approximately the progressive capability of blockchain withinside the discipline of engineering.

Discussion

The effects of the studies are very robust to signify that blockchain generation is surprisingly efficient, dependable and steady in facts transmission in the engineering structures. As a count of fact, incorporation of blockchain reduced community latency, improved throughput, reduced lack of packets and unauthorized get right of entry to compared to standard centralized structures. These findings coincide with the preceding studies, which perceive the immutable ledger of blockchain,

disbursed validating structures, and automatic clever contracts as the important thing factors in making sure the integrity of the information and the reliability of the operations (Dorri et al., 2017; Xu et al., 2019; Sharma et al., 2021). In theory, the paper validates the decentralized systems as capability answers to the vulnerabilities associated with single-factor failures, that have been extensively debated withinside the cybersecurity and dispensed structures literature (Swan, 2015; Reyna et al., 2018). Moreover, real-time tracking and records acquisition had been found out because of the mixing of IoT devices, which proved the synergy among blockchain and IoT in adaptive and self sufficient engineering structures (Li et al., 2019; Abeywardena et al., 2021). The empirical findings of the examine additionally display that the clever settlement talents do now no longer handiest growth automation however additionally toughen the governance and compliance withinside the engineering operations, ultimate the distance among the blockchain theoretical ideas and the engineering practice.

Conclusion

Conclusively, blockchain technology is a game-changer in ensuring the security of the transmission of data in the engineering systems. The research reveals that blockchain-based protocols are much better than the conventional centralized communication-based networks in reducing latency, streamlining throughput reduction, packet integrity, detection, and mitigation of anomalies, and prevention of unauthorized access. The combined use of smart contracts and IoT devices promotes the effectiveness and reliability of the operations even more, as it provides a constant tracking of the information and automatic validation of the data that has been transferred. Generally speaking, blockchain represents a powerful, decentralized, and immutable structure and, therefore, can be viewed as a central component of engineering networks of the contemporary era that demand safe, transparent, and efficient data flow. It is the conclusions of these studies that inform what is needed; the adoption of blockchain as a technological novelty, but as a strategic enabler of resilient and intelligent engineering systems.

Recommendations

According to the results, it is possible to derive a number of policy and operational recommendations. First, the implementation of the blockchain-based protocols in the essential data transmission schemes in the engineering organizations and smart infrastructure authorities must be focused on problem areas in the high-risk areas of the industry management, like industrial automation, smart grid, and infrastructural surveillance. Second, regulatory bodies are to develop a set of guidelines and standards of blockchain implementation, with the focus on interoperability, data privacy, and compliance with cybersecurity requirements. Third, the company should invest in capacity building and training engineers and IT professionals to handle systems powered by blockchain. Fourth, hybrid blockchain systems and off-chain storage systems need to be promoted to cover the issue of scalability and large volumes of data. Last but not least, administrative and structural stakeholders are advised to facilitate pilot projects and demonstration projects to test blockchain functionality in a variety of engineering situations and enable evidence-based scaling and adoption techniques. All of these measures will help to build resilient, secure, and efficient networks of engineering, which can serve larger objectives of digital transformation and smart infrastructure governance.

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