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Blockchain and zero-trust identity management system for smart cities and IoT networks

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Abstract
The rapid proliferation of IoT devices and the development of smart cities necessitate robust identity management systems to address trust and security challenges in interconnected environments. This paper explores integrating blockchain technology and zero-trust principles as a transformative approach to identity management in IoT ecosystems. Blockchain's decentralized and immutable architecture ensures secure data exchange and identity verification, while zero-trust principles enforce continuous authentication and granular access control. The review highlights current frameworks, identifies scalability, privacy concerns, and integration complexities, and examines emerging solutions, including lightweight consensus mechanisms, AI-driven enhancements, and interoperability standardization. Recommendations are provided to guide the implementation of these technologies, and research directions are outlined to address existing gaps. By leveraging the synergy between blockchain and zero-trust, this paper envisions a secure and sustainable framework for the future of smart cities and IoT networks.

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1. Introduction

Smart cities and the Internet of Things (IoT) networks are at the forefront of technological innovation, promising transformative changes in urban environments (Vermesan & Friess, 2013) [35]. These systems integrate interconnected devices, infrastructure, and services to enhance urban efficiency, sustainability, and quality of life. The potential applications of these technologies are vast, from intelligent traffic management and energy-efficient grids to automated healthcare systems and enhanced public safety. However, their success heavily relies on secure and reliable communication across distributed and heterogeneous networks (Appio, Lima, & Paroutis, 2019) [7].

Trust and security are pivotal challenges in IoT-based smart cities. The interconnected nature of these systems makes them inherently susceptible to threats such as unauthorized access, data breaches, and cyberattacks (Ismagilova, Hughes, Rana, & Dwivedi, 2022) [18]. Traditional security models, often reliant on perimeter-based defenses, fail to address IoT environments' dynamic and decentralized nature. Smart cities risk operational inefficiencies, privacy violations, and compromised public safety without robust mechanisms to establish trust and authenticate devices (Ahmad & Zhang, 2021) [4].

Blockchain and zero-trust identity management systems emerge as transformative solutions to these pressing issues. Blockchain offers a decentralized, tamper-proof ledger for secure data exchange, eliminating the reliance on central authorities (Boughdiri, Abdellatif, & Guegan, 2023) [12]. On the other hand, zero-trust frameworks operate on the principle of strict verification, assuming that no user, device, or system is inherently trustworthy. Together, these technologies hold the potential to redefine trust and

security paradigms in smart cities, ensuring the seamless and safe operation of IoT ecosystems.

This review explores the integration of blockchain and zero-trust identity management systems in the context of smart cities.

It examines how these technologies address critical trust and security challenges, evaluates current frameworks, and highlights emerging solutions. By aligning with ongoing smart city development projects, this paper provides timely insights into the practical application of these technologies, offering recommendations for future research and implementation.

2. Theoretical Background

2.1 Blockchain Technology

Blockchain is a decentralized digital ledger that records transactions securely across a network of nodes. Its primary principles—decentralization, immutability, and consensus—make it a ground-breaking technology for addressing the trust deficits inherent in modern digital ecosystems (Pilkington, 2016) [3]. Decentralization ensures that no single authority controls the network, reducing the risks associated with central points of failure. Immutability guarantees that once data is recorded on the blockchain, it cannot be altered or tampered with, thereby ensuring data integrity. Finally, consensus mechanisms, such as proof of work or proof of stake, facilitate agreement among network participants on the validity of transactions, ensuring trust without intermediaries (Sunyaev & Sunyaev, 2020) [33].

The application of blockchain in IoT and smart cities is multifaceted. It provides a secure and transparent mechanism for data exchange between devices in IoT networks, mitigating risks associated with unauthorized access and tampering. In smart cities, blockchain can enhance supply chain management, energy distribution, and public service delivery applications (Majeed *et al*., 2021) [20]. For instance, blockchain enables peer-to-peer energy trading in energy grids, allowing households to sell surplus electricity securely. In public governance, transparency can be improved by securely recording and verifying citizen interactions, such as voting or identity verification.

2.2 Zero-Trust Identity Management Systems

Zero-trust is a security paradigm that operates on the principle of "never trust, always verify." Unlike traditional models that rely on implicit trust within a network perimeter, zero-trust assumes that all entities—whether inside or outside the network—are potential threats. The core tenets of this approach include strict access controls, continuous verification of identities, and micro-segmentation to limit access to specific resources based on contextual factors such as user behavior and location (Kang, Liu, Wang, Meng, & Liu, 2023) [19].

The application of zero-trust frameworks in IoT environments addresses critical vulnerabilities associated with traditional identity management systems. These legacy systems often depend on static credentials or centralized identity repositories, which are prone to breaches and inefficiencies in distributed environments (Daniel, 2023). Zero-trust solutions enhance security by implementing granular access policies and leveraging advanced authentication techniques, such as multi-factor authentication and biometric verification. This ensures that only verified entities can access sensitive resources, even within the same network (Ghasemshirazi, Shirvani, & Alipour, 2023) [12].

2.3 Synergies Between Blockchain and Zero-Trust

The integration of blockchain and zero-trust frameworks creates a complementary security model that addresses key challenges in IoT and smart cities. Blockchain's decentralized ledger ensures the secure storage and sharing of identity-related data, eliminating the reliance on vulnerable centralized databases. Meanwhile, zero-trust frameworks provide the operational framework for enforcing strict identity verification and access control policies (Ray, 2023) [32].

A notable synergy lies in blockchain's ability to enhance identity management through self-sovereign identity systems. These systems empower users to maintain control over their identity data, storing it securely on the blockchain while sharing only necessary information with requesting parties. When combined with zero-trust principles, such systems enable real-time verification of identity and contextual factors, ensuring robust access control (Van Wingerde, 2017) [34].

Another area of alignment is in auditing and accountability. Blockchain's immutable record-keeping complements zero-trust's focus on monitoring and logging user activities. Together, these technologies provide a comprehensive mechanism for tracing and mitigating security incidents, ensuring transparency and accountability across IoT networks. In conclusion, the convergence of blockchain and zero-trust offers a holistic approach to addressing the trust and security challenges in IoT ecosystems and smart cities. Their integration not only enhances operational efficiency but also sets a robust foundation for the sustainable growth of these interconnected systems (Wang & De Filippi, 2020) [36].

3. Current Frameworks and Challenges

3.1 Review of Existing Blockchain-Based Identity Management Systems

The adoption of blockchain-based identity management systems has gained traction in IoT and smart cities, addressing critical issues such as trust, data security, and operational transparency. These frameworks leverage blockchain's decentralized architecture to manage secure, immutable, and transparent identity data. Prominent examples include self-sovereign identity systems, where users maintain control over their digital identities without reliance on centralized authorities. Such systems allow users to share only the necessary credentials while securing their core identity data on a distributed ledger (Ike *et al*., 2021; Oladosu *et al*., 2022c) [23].

In smart cities, blockchain-based frameworks have been applied to various domains, including citizen identification, access control for public services, and device authentication. For instance, blockchain facilitates secure interactions between IoT devices in urban settings, enabling seamless communication between smart meters, sensors, and city management systems. These frameworks reduce operational complexities and enhance data integrity by eliminating the need for intermediaries (Oladosu *et al*., 2022b) [22].

Despite their potential, these systems remain in the developmental stage, with most implementations limited to pilot projects and proof-of-concept deployments. While they showcase the feasibility of blockchain-based identity management, their real-world scalability and reliability in complex ecosystems like smart cities remain a significant

challenge (Afolabi, Ige, Akinade, & Adepoju, 2023; Onoja & Ajala, 2023b) [24, 28].

3.2 Challenges Faced

One of the most pressing challenges of integrating blockchain into IoT and smart cities is scalability. As the number of devices and transactions in these ecosystems grows, blockchain networks' computational and storage requirements increase significantly. Public blockchains like Bitcoin and Ethereum often struggle with high latency and limited transaction throughput, hindering real-time communication and processing in IoT systems.

IoT networks, characterized by their resource-constrained devices, face difficulties in supporting the computationally intensive processes required by traditional blockchain architectures. Consensus mechanisms like proof of work demand substantial processing power, which is impractical for many IoT devices. While alternative consensus algorithms, such as proof of stake and delegated proof of stake, aim to address these issues, their widespread adoption and effectiveness in large-scale environments remain uncertain (Austin-Gabriel, Hussain, Ige, Adepoju, & Afolabi, 2023; Oladosu *et al*., 2022a) [13, 23].

While blockchain's transparency is a strength, it also raises concerns regarding data privacy. The immutability of blockchain records means that once data is stored, it cannot be altered or deleted, posing challenges in complying with privacy regulations like the General Data Protection Regulation (GDPR). These laws require mechanisms for data erasure and user consent, which are difficult to implement in traditional blockchain systems (Adepoju *et al*., 2022) [1]. Furthermore, the public nature of many blockchain platforms can expose sensitive data to unauthorized access, even if encryption is applied. Ensuring that identity information remains private while maintaining the benefits of blockchain's transparency requires innovative solutions, such as advanced cryptographic techniques like zero-knowledge proofs (Onoja & Ajala, 2022) [27].

The lack of global standards for blockchain implementation poses another challenge on the regulatory front. Smart city projects, often spanning multiple jurisdictions, must navigate a complex web of regulatory requirements. This fragmentation hinders the seamless adoption of blockchain-based identity management systems across borders, limiting their scalability and effectiveness.

The integration of blockchain with IoT devices is another significant hurdle. IoT devices often operate with limited processing power, memory, and energy resources, making it difficult to handle computational demands for blockchain operations. Additionally, these devices are highly diverse, encompassing various manufacturers, protocols, and communication standards (Hussain, Austin-Gabriel, Ige, Adepoju, & Afolabi, 2023) [13]. Achieving interoperability between blockchain frameworks and heterogeneous IoT devices is a complex and resource-intensive task. Moreover, IoT devices are frequently deployed in dynamic environments, where they face issues such as intermittent connectivity, hardware malfunctions, and security vulnerabilities. Ensuring that blockchain-based identity management systems can adapt to these challenges while maintaining their performance and reliability is an ongoing area of research (Afolabi, Hussain, Austin-Gabriel, Adepoju, & Ige, 2023; Onoja, Ajala, & Ige, 2022) [13, 27].

The integration of blockchain into IoT and smart cities, while promising, faces significant hurdles. Scalability and latency remain critical barriers, particularly for real-time applications. Privacy concerns and regulatory constraints further complicate adoption, requiring solutions that balance transparency with data protection. Lastly, IoT devices' diverse and resource-constrained nature poses integration challenges that demand tailored approaches to ensure interoperability and efficiency. Addressing these challenges is essential for the widespread adoption of blockchain-based identity management systems. Innovations in consensus mechanisms, privacy-preserving techniques, and device interoperability are vital for realizing the potential of these frameworks in enabling secure and trusted smart city ecosystems (Akinade, Adepoju, Ige, & Afolabi, 2023; Oladosu *et al*., 2021b) [1, 21].

4. Emerging Solutions and Future Directions

4.1 Novel Frameworks Combining Blockchain and Zero-Trust Principles

Emerging solutions are increasingly focusing on integrating blockchain technology with zero-trust principles to address the security and trust challenges in IoT ecosystems and smart cities. These frameworks leverage blockchain's decentralized architecture to securely store and manage identity data while implementing zero-trust policies to enforce strict access control and verification (Oladosu *et al*., 2023) [24].

One innovative framework involves the use of self-sovereign identity systems. These systems enable individuals and devices to maintain ownership of their digital identities on a distributed ledger, allowing selective sharing of verified credentials without exposing sensitive data. The integration of zero-trust policies ensures that every access request is authenticated and authorized based on real-time contextual analysis. This combination enhances both privacy and security while minimizing reliance on centralized authorities (Oladosu *et al*., 2023) [24].

Another notable development is the adoption of blockchain-based attribute-based access control (ABAC) systems. These systems use blockchain to securely manage and validate the attributes of users and devices, which are then used to enforce zero-trust policies. By decentralizing attribute storage and verification, ABAC frameworks reduce the risks of single points of failure and provide a scalable approach to access management in dynamic and distributed environments (Ige *et al*., 2022).

4.2 Use Cases in Ongoing Smart City Projects

Several smart city projects worldwide are exploring the practical application of blockchain and zero-trust frameworks. For example, in energy management, blockchain-based systems enable secure peer-to-peer energy trading between households with renewable energy sources. Zero-trust policies ensure that only verified participants can engage in transactions, safeguarding the system against fraud and unauthorized access (Austin-Gabriel *et al*., 2021) [9].

In public transportation, blockchain is being used to streamline ticketing and access control, while zero-trust frameworks validate user identities and ensure that only authenticated individuals can access services. These systems also provide immutable records of transactions, enhancing transparency and accountability.

Healthcare is another area where these technologies are making strides. Blockchain secures patient data and medical records, while zero-trust frameworks ensure that only

authorized personnel and devices can access sensitive information. This combination protects patient privacy and improves trust in digital health systems. These use cases highlight the potential of integrating blockchain and zero-trust to enhance operational efficiency, security, and trust in smart city services. However, their full-scale implementation requires addressing several research gaps and technical challenges (Hussain *et al*., 2021; Onoja & Ajala, 2023a) [28. 13].

4.3 Research Gaps and Potential Areas for Innovation

One of the primary challenges in integrating blockchain with IoT is the resource-intensive nature of traditional consensus mechanisms like proof of work. Researchers are developing lightweight consensus algorithms tailored for IoT environments to overcome this limitation. Protocols such as proof of authority and proof of elapsed time offer lower computational overhead, making them suitable for resource-constrained devices. Further innovations in this area are critical to ensuring the scalability and efficiency of blockchain frameworks in IoT networks (Akinade, Adepoju, Ige, Afolabi, & Amoo, 2022) [1, 23].

Artificial intelligence (AI) has significant potential to enhance the security and functionality of blockchain-based identity management systems. AI algorithms can analyze large volumes of data to detect anomalies and predict potential security threats in real time. Machine learning models can also improve identity verification accuracy by analyzing behavioral patterns and contextual factors. Integrating AI into blockchain and zero-trust frameworks can enable more adaptive and resilient security systems, capable of responding to evolving threats in dynamic environments (Ike *et al*., 2023).

The lack of standardized protocols and frameworks for blockchain and zero-trust integration poses a major barrier to their widespread adoption. Interoperability between different blockchain platforms and IoT devices is essential for creating cohesive smart city ecosystems. Standardization efforts should focus on defining common data formats, communication protocols, and security requirements to enable seamless interaction between heterogeneous systems. Collaborative initiatives involving governments, industry stakeholders, and academic researchers are crucial to achieving this goal (Oladosu *et al*., 2021a) .

The convergence of blockchain and zero-trust principles represents a significant leap forward in addressing the security and trust challenges of IoT networks and smart cities. By enabling decentralized, secure, and scalable identity management systems, these technologies pave the way for more resilient and efficient urban environments. However, realizing their full potential requires sustained research, development, and collaboration efforts. Lightweight consensus mechanisms must be refined to ensure compatibility with resource-constrained IoT devices. AI-driven innovations can enhance the adaptability and robustness of security frameworks. Meanwhile, standardization efforts are essential to achieve interoperability and scalability in diverse smart city projects.

4. Conclusion and Recommendations

This review highlights the transformative potential of integrating blockchain and zero-trust identity management systems in IoT ecosystems and smart cities. The decentralized and immutable nature of blockchain addresses critical trust issues by providing secure, transparent, and tamper-proof mechanisms for identity management and data exchange. Meanwhile, zero-trust principles enforce rigorous verification and granular access control, effectively addressing vulnerabilities associated with traditional security frameworks. Together, these technologies offer a robust solution to the growing security demands of interconnected environments.

Despite their promise, significant challenges persist. Scalability and latency issues in blockchain systems hinder real-time applications in large-scale IoT networks. Privacy concerns, particularly in adhering to data protection regulations, complicate the implementation of blockchain's inherently transparent architecture. Additionally, IoT devices' diverse and resource-constrained nature poses integration and interoperability challenges. Addressing these issues is essential for unlocking the full potential of these technologies.

The following strategies are recommended to implement blockchain and zero-trust frameworks effectively in IoT ecosystems. Blockchain systems tailored for IoT must prioritize scalability and efficiency. Lightweight consensus mechanisms, such as proof of authority or delegated proof of stake, can reduce computational overhead and improve transaction throughput. Hybrid blockchain architectures combining public and private networks can also balance scalability, security, and accessibility.

Addressing privacy concerns requires advanced cryptographic methods, such as zero-knowledge proofs and secure multi-party computation, which allow data verification without revealing sensitive information. Self-sovereign identity systems, where users retain control over their data, should be prioritized to enhance user privacy and compliance with regulations. Achieving interoperability between blockchain frameworks and heterogeneous IoT devices requires standardized protocols and data formats. Collaborative efforts involving industry stakeholders, governments, and academic researchers should focus on creating unified frameworks that enable seamless integration and communication across diverse systems.

Integrating artificial intelligence into blockchain and zero-trust systems can significantly improve security. AI-powered anomaly detection and adaptive access control mechanisms can enhance real-time threat detection and response, making IoT ecosystems more resilient to evolving cyber threats. Harmonizing policies and regulations across jurisdictions is critical for the widespread adoption of blockchain and zero-trust frameworks. Governments should work towards creating consistent guidelines that address data privacy, security standards, and compliance requirements, ensuring the compatibility of smart city initiatives globally.

Future research should focus on addressing the key challenges outlined in this review. Efforts to develop more efficient and resource-friendly blockchain solutions are critical for large-scale IoT applications. Privacy-preserving techniques must evolve to balance transparency with compliance requirements, ensuring user trust and regulatory adherence. Additionally, research into AI-driven enhancements for blockchain and zero-trust frameworks can offer new ways to optimize performance and security. Another essential area of investigation is policy harmonization and governance models for smart cities. Developing frameworks that align technological advancements with legal and ethical standards will ensure

these ecosystems' sustainable and responsible growth.

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