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Blockchain Architectures for the Digital Economy: Trends and Opportunities

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Abstract: The digital economy, driven by information and communication technologies (ICT), has profoundly transformed in recent decades. The digitalization of society has given rise to an economic environment in which information, connectivity, and innovation play fundamental roles. In this context, a technology that has emerged as a fundamental pillar of the digital economy is the chain of blocks, commonly known as blockchain. Blockchain is a technology that has revolutionized the way online data and transactions are managed and shared. Through its ability to create secure, transparent, and decentralized ledgers, blockchain has paved the way for the digital economy, facilitating trust in digital transactions and enabling various applications ranging from cryptocurrencies to supply chain management and intellectual property. This study will delve into blockchain and its influence on the digital economy. It will explore how this technology has reshaped how companies interact, how consumers access services, and how new business models are developed in a constantly evolving digital environment. Additionally, the challenges and opportunities that blockchain presents in the context of the digital economy will be analyzed, and how it is helping to shape the future of business and society in general. As the exploration of blockchain and its impact on the digital economy progresses, it becomes evident how these two forces converge, generating a promising digital landscape full of significant opportunities and transformations. This phenomenon is consistently supported by a growing body of research and analysis, which underlines the growing influence of blockchain on the global economy. The dynamic interplay between these two spheres, blockchain and the digital economy, is constantly evolving and offers an exciting glimpse into the future regarding innovation and disruption across a wide range of sectors. As a result, significant opportunities are looming for those seeking to understand and capitalize on these emerging trends. Throughout this study, the current trends and most intriguing perspectives that shape this landscape will be broken down, offering a deeper insight into how blockchain and the digital economy are shaping an extraordinary digital future.

Keywords: blockchain; blockchain architecture; digital economy; emerging technologies; online transactions

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1. Introduction

The global economy has undergone a profound transformation driven by significant technological advances in an increasingly digitalized world. One of the most prominent catalysts of this economic revolution is blockchain technology. As Don Tapscott, author of the book *Blockchain Revolution*, notes, this technology has become "a trusted platform" that is fundamentally redefining how transactions are carried out and how digital assets are managed in today's digital economy [1].

Blockchain, originated by Bitcoin cryptocurrency in 2009, has transcended its initial application and has become a driving force in the digital economy. By offering a distributed, transparent, and tamper-resistant ledger, blockchain has enabled greater trust in online transactions, creating new business models and driving innovation in various sectors.

A study by [2] highlights how blockchain transforms supply chains, asset management, and financial operations while improving efficiency and reducing costs. Additionally, blockchain technology has enabled the creation of digital tokens and non-fungible assets (NFTs), revolutionizing how digital assets and intellectual property rights are owned and traded.

The digital economy points to a set of economic activities carried out using digital technologies, especially those related to information and communications, thus implying the transformation of traditional processes in various businesses, which adapt to a digitalized environment, for example, the widespread use of the internet, e-commerce, mobile applications, and electronic data processing. The speed at which information travels and global connectivity are crucial elements in this new form of economy, allowing for faster and more efficient decision-making [3,4].

In essence, the digital economy involves transforming economic activities through the intensive use of digital technologies. This shift towards digital has not only impacted the way transactions are carried out but has also driven innovation in products and services, thus redefining traditional market dynamics and reflecting the adaptation of economic activities to a digitalized environment, where technology becomes the backbone of everyday business interactions [5].

The digital economy is distinguished by the constant growth of economic transactions and operations that are carried out online. In the words of Erik Brynjolfsson and Andrew McAfee, authors of the book *The Second Machine Age*, this new economic era is characterized by an "explosion of digital innovations" that are transforming the way we interact with the business and economic world [6].

With the emergence of e-commerce platforms, streaming services, digital banking, and various online applications and services, the digital economy has experienced exponential growth in recent decades. This digital revolution has redefined how businesses and consumers relate to each other and has generated new business opportunities on a global scale.

In this context of constant evolution, blockchain technology has stood out as a cornerstone that supports and enhances the digital economy [7]. As this technology continues to mature and develop, its impact on the online economy becomes increasingly evident. On the other hand, consensus algorithms are also constantly evolving to adapt to the changing needs of the digital economy, such as scalability, energy efficiency, and interoperability between different blockchain networks [8]. In addition, they are driving innovation in business models and creating entirely new economic opportunities, such as DeFi (Decentralized Finance) and NFT (Non-Fungible Tokens).

Blockchain has a significant impact on these digital technologies due to its ability to offer a revolutionary method of decentralized registration and verification, using a data structure in chained blocks, each one linked to the previous one in an immutable and secure way, eliminating the need for intermediaries in the digital transactions, which not only provides an unprecedented level of security and trust but also speeds up operations by reducing the execution times of any transaction. Blockchain technology influences how digital data are managed and shared by offering an efficient model resistant to data manipulation, resulting in a greater integrity and reliability of information, extending this impact through various digital economy applications [9].

In the context of the digital economy where trust is essential, blockchain architectures act as a fundamental pillar of digital technologies due to their ability to offer a secure, transparent, and decentralized system of registration and verification of transactions, which not only increases security by making data manipulation extremely difficult but also streamlines processes by providing a distributed consensus without relying on a central authority [10–13].

The exploration of blockchain architectures in the digital economy is revealed as a prevailing need due to the fundamental characteristics that this technology brings to the digital environment. One of the main motivations lies in the search for greater security and transparency in digital transactions, guaranteeing data integrity and significantly reducing the risk of fraud, providing essential efficiency in a dynamic and fast digital economic environment, facilitating the implementation of smart contracts, and allowing the automation of commercial agreements without the need for additional intermediaries.

This study will set the stage for further explorations of the impact of blockchain architectures on the digital economy, examining the many facets of this symbiotic relationship, from how blockchain is revolutionizing digital asset management and intellectual property to how it is driving innovation in business models and the creation of new economic paradigms [14–17]. Through this analysis, we seek to shed light on the opportunities and challenges this convergence between the digital economy and blockchain architectures poses for present and future technologies [18–20].

2. Fundamentals of Blockchain Architectures

Blockchain is a data structure that enables the secure storage and management of digital records on a distributed network. One of the most influential documents introducing the blockchain concept is Satoshi Nakamoto's article, "Bitcoin: A Peer-to-Peer Electronic Cash System" [21]. In this article, Nakamoto proposed creating a completely decentralized and trustworthy digital cash system.

Blockchain is based on its ability to maintain an immutable and transparent record of transactions, making it a unique technology. Its operation is similar to a chain of blocks, where each block contains a set of verified transactions. These blocks are interconnected by cryptographic functions that guarantee the integrity and sequence of the data. This blockchain structure ensures the reliability of transactions and their resistance to any manipulation attempt [22,23].

In the blockchain process, various actors play crucial roles in ensuring efficient and secure operation:

- Nodes: These are active participants in the blockchain network. Their principal function is to validate, record, and maintain transactions on the blockchain. Each node owns a complete copy of the blockchain ledger and participates in verifying transactions.
- Miners: These are particular nodes that play a central role in the security and integrity of the blockchain. They compete with each other to add a new block to the chain. To achieve this, they solve complex cryptographic problems depending on the specific consensus algorithm of the blockchain they are using [24].
- Users: These are the entities that carry out transactions on the blockchain. These users can be individuals and corporate entities actively participating in the digital economy.

Together, these actors work harmoniously to ensure the blockchain operates efficiently and securely, making it an essential technology in today's digital economy. Decentralization in blockchain is a fundamental principle. Unlike traditional centralized systems like banks, blockchain operates on a distributed node network, eliminating the need for a central trusted entity. This decentralized approach provides greater security by avoiding single points of failure and censorship.

Security in the blockchain is based on robust cryptographic techniques. Cryptographic algorithms protect information stored in blocks, making the altering or falsifying of the data virtually impossible. This guarantees the reliability of the transactions and the integrity of digital assets. Immutability, another essential pillar of a blockchain, means that, once information is recorded in a block, it cannot be modified without the consensus of the majority of nodes in the network. This scenario creates a reliable and auditable historical record in various applications, from cryptocurrencies to smart contracts.

Blockchain architectures form a distinctive and fundamental aspect of this constantly evolving technology. Over time, several architectures have emerged, each with its own characteristics and specific applications. The most prominent architectures are public, private, consortium, and hybrid blockchains, each designed to address particular needs and challenges in different contexts [25–27].

- Public Blockchain: In this type of blockchain, the network is open to anyone who wants to join. There are no restrictions on participation, and anyone can read, write, and validate transactions. Public blockchains are entirely transparent and are generally used in applications such as cryptocurrencies, where accessibility and decentralization are essential.
- Private Blockchain: Unlike public blockchains, these restrict access to a select group of participants. Only authorized nodes can participate and validate transactions. This architecture is used in enterprise applications requiring control and privacy, such as supply chain tracking systems, electronic medical records, etc. [28,29].
- Consortium Blockchains: They are a hybrid between the public and private. A group of predefined actors operates the network and shares the authority to validate transactions. This architecture suits companies and organizations that want to collaborate in a trusted environment, such as shared records management in the financial sector.
- Hybrid Blockchains: Hybrid blockchains combine elements of several architectures to take advantage of the advantages of each. For example, a hybrid network may use a public blockchain for certain transactions and a private blockchain for others. This flexibility allows us to adapt to various needs and use cases.

3. Evolution of Blockchain Architectures

The history of blockchain architecture begins with the creation of Bitcoin in 2008 by Satoshi Nakamoto, who presented the first implementation of blockchain as a solution to trust issues in online transactions. Bitcoin introduced the concept of a decentralized cryptocurrency and public ledger, allowing people to conduct peer-to-peer transactions without intermediaries [30,31].

Blockchain architecture is an innovative framework based on a decentralized network characterized by the ability to secure and validate transactions transparently and securely. It comprises blocks of data linked chronologically and encrypted using cryptographic algorithms. Each block contains a set of confirmed transactions and a unique hash that connects it to the previous block, thus creating an immutable chain. This type of architecture provides unparalleled integrity to the stored information, as altering one block would require the modification of all subsequent blocks, which is virtually impossible due to the inherent immutability of the chain [32,33].

Decentralization is one of the fundamental pillars of the blockchain architecture as it is distributed among different participating nodes, each maintaining a complete copy of the chain. The validation of transactions is developed through a distributed consensus, where nodes agree on the validity of a transaction before it is added to the block [34]. This approach eliminates the need for a central authority and increases resistance to malicious attacks. In addition, the different architectures used under blockchain technology allow the participation of any node that meets the requirements, thus promoting inclusion and transparency [35,36].

Smart contracts, on the other hand, are a distinctive feature among blockchain architectures. They are nothing more than autonomous, self-executing programs that are automatically activated when certain predefined conditions are met. They are the ones that allow the blockchain to work without the need for intermediaries.

A blockchain stores considerable data, and its size increases as information is added. Therefore, it is essential to have a mechanism that allows efficient queries, making it possible to perform queries without downloading all of the stored information. A Merkle Hash Tree is used in the Bitcoin blockchain to address this challenge, allowing different information pieces to be organized and stored independently [37]. The main advantage of this type of structure lies in its ability to consult some aspects without requiring the downloading of all the tree's information. In [38], there is a detailed description and efficient implementation of this type of tree.

Figure 1 shows the information contained in each block of the Bitcoin blockchain; in the header, there are the following:

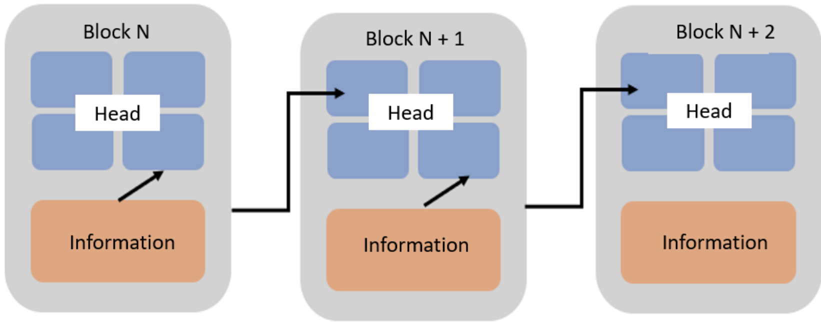

Figure 1. Bitcoin blockchain architecture. Own elaboration.

A hash value of the previous block: this value allows the sequential linking of the blocks, thus forming an immutable chain.

- Timestamp: The timestamp allows for identifying when the block was created.
- Nonce: This value is found by brute force during the mining process.
- Root hash: This root hash serves as a reference for all the information in the block. It allows efficient and secure queries about the content of the block.
- Moreover, in the other part of the block is Information: This is the additional information, which, in the case of Bitcoin, is the transactions made with the cryptocurrency. Additionally, one of these transactions rewards the miner who created the block. This reward decreases by half every 210,000 blocks, equivalent to approximately four years. In 2009, the reward was 50 bitcoins, currently at approximately 12.5 bitcoins.

As Bitcoin gained popularity, its success inspired others to explore the possibilities of blockchain technology in different applications beyond cryptocurrencies. One of the first notable evolutions was the introduction of Ethereum in 2015 by Vitalik Buterin and other collaborators [39,40]. Ethereum took blockchain technology a step further by enabling the creation of smart contracts, which are autonomous programs that run on the blockchain and can automate agreements and business processes.

Vitalik Buterin, recognized as the creator of Ethereum and co-founder of the Ethereum Foundation, conceived of Ethereum as a decentralized computing platform with the ability to allow any individual to create, store, and run decentralized applications, known as DApps, based on smart contracts [41].

To better understand how Ethereum works, it is essential to analyze its underlying structure. An Ethereum blockchain network is a decentralized peer-to-peer (P2P) network comprising multiple Ethereum clients representing network nodes. Each Ethereum client is a node capable of verifying new transactions, executing smart contracts, and processing the creation of new blocks on the chain. These Ethereum clients are distributed across thousands of computers or devices connected to the Internet, forming a decentralized network through which the platform's operations are managed.

It is important to highlight that the essential component of this decentralized network is the Ethereum Virtual Machine (EVM) and its execution environment, which is deployed on the P2P network for the execution of smart contracts. At its core, the EVM is an execution engine that allows smart contracts to operate consistently and securely on the Ethereum network. The following visual representation shows how this P2P network is organized (Figure 2). In this structure, each node in the P2P network owns a complete copy of the Ethereum ledger and plays a critical role in validating and processing transactions within the platform. This distributed and decentralized design is one of the key features that makes Ethereum a unique and powerful platform in blockchain technology.

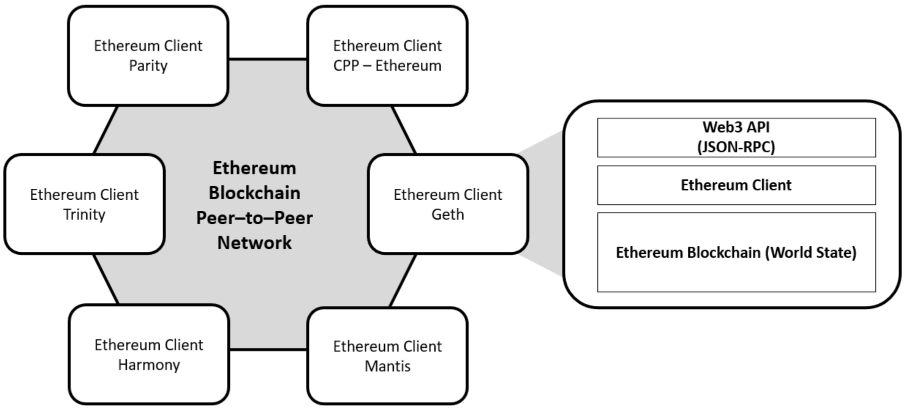

Figure 2. Ethereum blockchain architecture. Own elaboration.

With the rise in Ethereum, new doors have opened for blockchain innovation. Numerous alternative projects and blockchains were created to address specific scalability, privacy, and functionality limitations. Some notable examples include Ripple (XRP) for cross-border payments and Hyperledger for enterprise applications.

In the business world, enterprise blockchain architectures began to take shape by introducing solutions such as IBM Blockchain and Microsoft BaaS (Figure 3). These platforms provided companies with tools and services to develop personalized blockchain applications adapted to their needs [42].

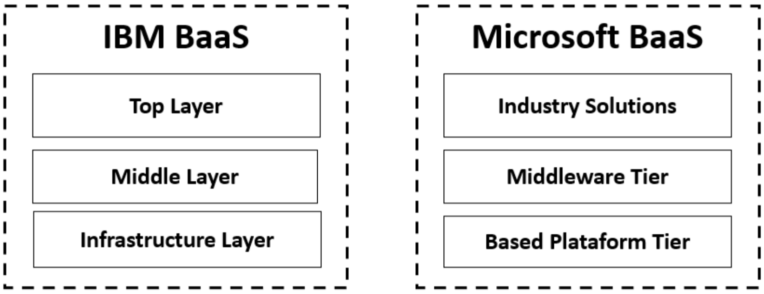

Figure 3. IBM BaaS and Microsoft BaaS architecture. Own elaboration.

The evolution of blockchain architectures also includes the emergence of public, private, and consortium blockchains. Public blockchains, such as Bitcoin and Ethereum, are accessible to anyone and are primarily used in financial and investment applications [43].

On the other hand, private blockchains restrict access and are used in enterprise environments to ensure privacy and confidentiality. Consortium blockchains are an intermediate-term where a select group of participants maintain the blockchain and share control.

Ref. [44] defines the blockchain architecture under exceptional characteristics such as irreversibility, decentralization, persistence, and anonymity, describing the functioning and structure of blockchains in the real world and focusing on the mining process during the validation and verification of the network. View Figure 4.

Authors such as the authors of reference [45] classify blockchain architectures into three main categories: public, private, and consortium. In the public architecture, information and access are always available to anyone. In the private architecture, information is only available to users of the same entity or company.

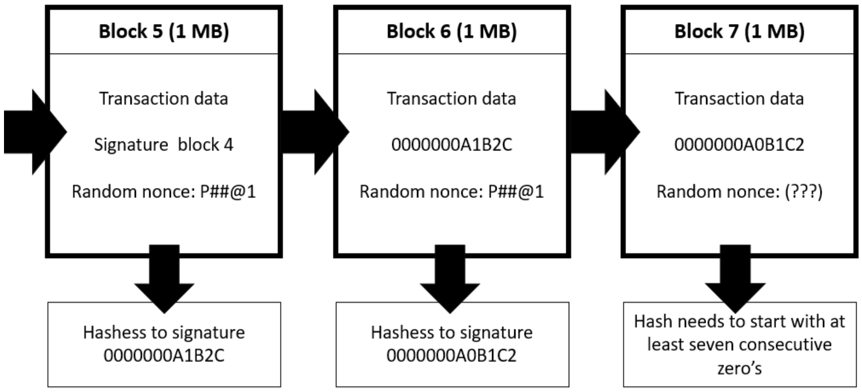

Figure 4. Source: own elaboration. Blockchain architecture under some exceptional features.

Finally, consortium architecture brings together a set of companies that operate in the same industry and require common ground to conduct transactions or share information. View Figure 5.

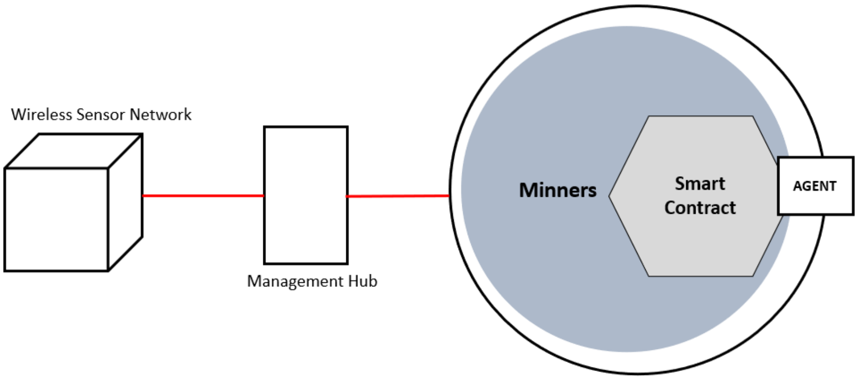

Figure 5. Source: own elaboration. Consortium architecture.

Ref. [46] proposed a blockchain architecture design for organizations, addressing security and confidentiality issues, providing audit services, and facilitating the connectivity of any company to a blockchain. View Figure 6.

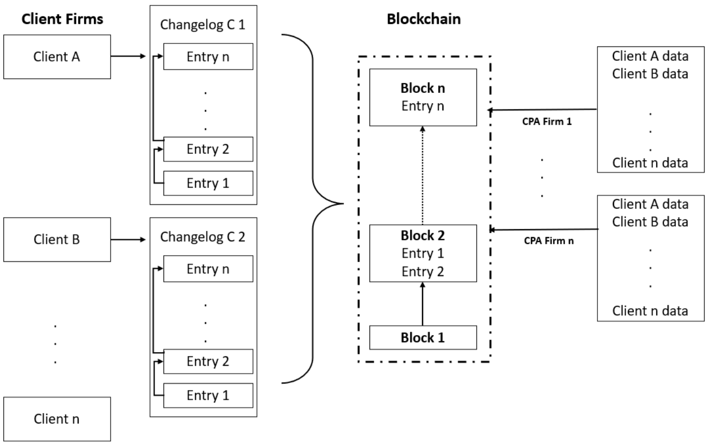

Figure 6. Source: own elaboration. Proposed a blockchain architecture design for organizations.

In Figure 7, refs. [47–49] show a reference architecture for a software system where the blockchain is one of the main components, explaining that, as a component, blockchain has unique properties and limitations, providing data storage, computing services, and communication services at the same time.

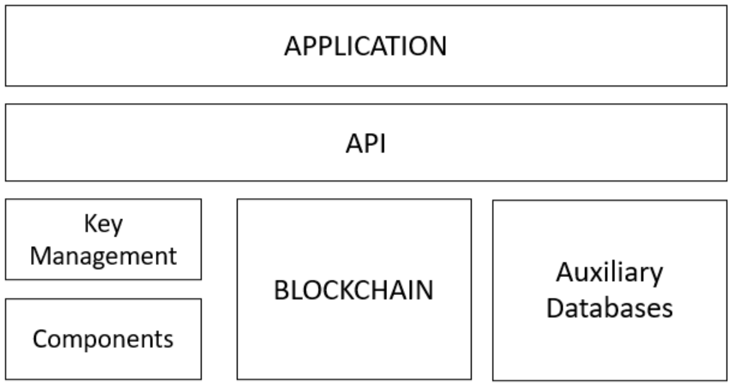

Figure 7. Source: own elaboration. A reference architecture for a Software System.

On the other hand, Ochoa and others proposed an architecture through which it is possible to identify fake news on social networks, alert readers, punish those who disperse false information, and reward those who publish truthful information. In this architecture, they consider each block as an object (Figure 8), so each transaction generated is considered a block, and, within each of them, the metadata extracted from the published news are stored.

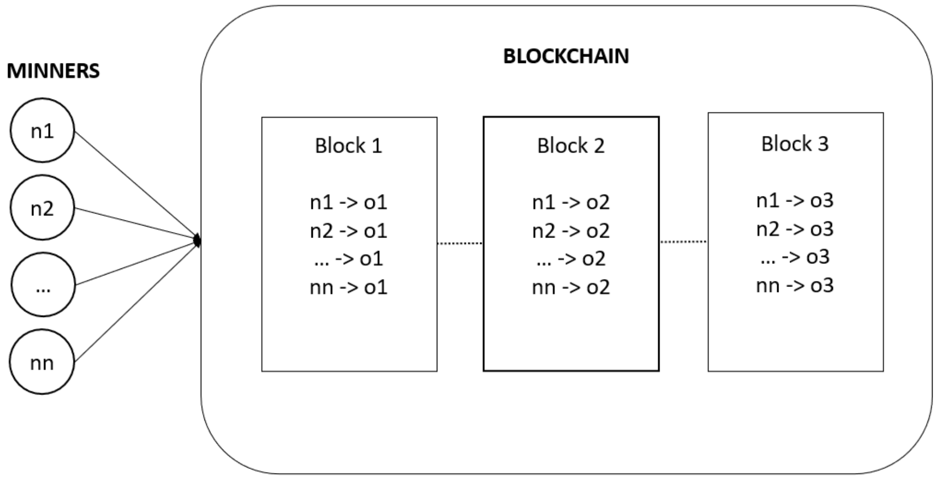

Figure 8. Source: own elaboration. Architecture through which fake news is identified on social networks.

Amazon has adopted a component-based architecture to implement its blockchain network, which uses the service provided by Hyperledger and runs on the Amazon Web Services (AWS) infrastructure (Figure 9). In this configuration, the blockchain network remains operational as long as active members are deactivated only when the last member decides to leave the network. Each node owned by a user on this network owns a local copy of the blockchain ledger, which contains a record of all transactions and maintains a global network state for the specific channels in which that node participates. It should be noted that this global state is constantly updated as new transactions are made on the network.

This component-based architecture approach, coupled with the utilization of Hyperledger services and AWS infrastructure, allows Amazon to manage its blockchain network efficiently and efficiently, ensuring a secure and up-to-date record of all transactions made on the blockchain platform. This type of architecture is fundamental in successfully implementing blockchain-based solutions in the business environment and contributes to transparency and reliability in business operations.

Today, blockchain architectures continue evolving with the development of scalability, interoperability, and governance solutions. Use cases are being explored in a wide variety of industries, from supply chain and healthcare to digital rights management and electronic voting.

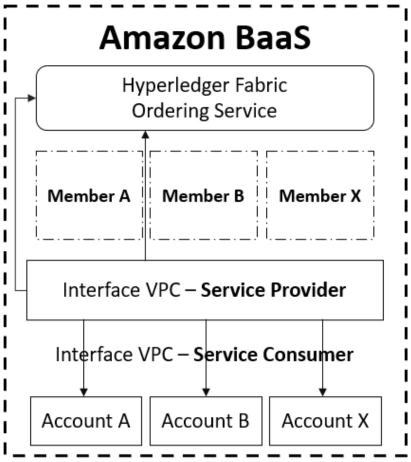

Figure 9. AWS architecture. Source: own elaboration.

4. Current Trends in Blockchain Architectures

The most recent trends in blockchain architecture show this technology's constant evolution and increasing adoption in various industries. In this context, significant trends and developments have been observed in recent years that have changed how blockchain networks are used and understood. Below are some of the most recent trends and developments in this area:

- Business Blockchain: One of the most notable trends is the growing adoption of blockchain in companies and organizations. Authors such as the authors of reference [1] have argued that blockchain has the potential to revolutionize the way transactions and contracts are carried out in the business environment. Specific blockchain architectures are being developed for enterprise applications that offer greater privacy, scalability, and efficiency [50,51].
- Interoperability: Interoperability between different blockchain networks is a significant trend. The projects are working on solutions that allow different blockchains to communicate and share information more seamlessly, facilitating collaboration and the transfer of assets between different platforms. Authors such as the authors of reference [52] have investigated solutions enabling fluid and secure communication between blockchains. Interoperability is considered crucial for the future of blockchains in the digital economy.
- Blockchains in the Cloud: Cloud service providers, such as AWS, Azure, and Google Cloud, offer managed blockchain services that simplify the implementation and management of blockchain networks. Simplifying the implementation makes the technology more accessible to businesses that want to take advantage of its benefits without the complexity of infrastructure management.
- Hybrid and Consortium Blockchains: Hybrid blockchain networks combine public and private blockchain elements and are gaining popularity. Authors such as the authors of reference [53] have pointed out that these architectures allow organizations to maintain control over certain aspects of their network while taking advantage of the security and decentralization of public blockchains.
- Smart Contracts and Defi Blockchain: Smart contract programming has become fundamental to many blockchains. Authors such as Szabo [54] coined the term "smart contract", and these are now used in a variety of applications, from decentralized financial services (DeFi) to identity management and more. Blockchain architectures must support the secure and efficient execution of these contracts. The DeFi ecosystem continues to grow and experiment with new blockchain-based financial applications. This scenario includes lending, decentralized exchanges, staking, and much more. DeFi has become an area of high growth and experimentation in cryptocurrencies.

- Blockchain and Non-Fungible Tokens (NFTs): The emergence of non-fungible tokens, representing unique and scarce digital assets, has given rise to new blockchain architectures and applications [55]. Authors such as the authors of reference [56] have explored how blockchain technology is used to support the ownership and authenticity of NFTs.
- Sustainability: Sustainability has become an important topic in the blockchain world due to the high energy consumption associated with some blockchains, such as Bitcoin [57]. Trends are leaning towards adopting cleaner energy sources and more efficient consensus solutions regarding energy consumption [58].
- Digital Identity: Digital identity management is another area that blockchain impacts. Decentralized identity systems allow people greater control over personal information and reduce identity theft risk.
- Blockchain as a Service (BaaS): BaaS offerings continue to expand, allowing businesses to take advantage of the benefits of blockchain without the need to build and maintain their infrastructure. This facilitates the adoption of blockchain in a variety of applications.
- Government and Regulation: As blockchain matures, governments and regulatory agencies are developing laws and regulations to address security, privacy, and taxes related to cryptocurrencies and blockchain networks. Authors such as the authors of reference [59] have discussed decentralized governance models for making decisions about updates and changes to the network.

Blockchain technology is used in various digital economy sectors to improve efficiency and transparency in the processes and security of operations. Some examples of real cases that currently work are as follows:

- Ripple uses blockchain to facilitate fast and secure international transfers between some banks.
- Walmart and IBM use blockchain to track the food supply chain, allowing faster response during product recalls. That is, blockchain technology is used as part of the logistics of these companies.
- Everledger is a London startup that uses blockchain technology to track the provenance of diamonds, thus ensuring authenticity and ethics in the supply chain.
- MedRec is a medical records management system that explores the use of blockchain technology to manage and share medical records securely and efficiently.
- Mediachain is a platform to register images and author content for multimedia works. It was recently acquired by Spotify.
- Power Ledger, an Ethereum-based project that allows us to buy and sell energy, is a a platform to create decentralized energy markets.

5. Application Opportunities in the Digital Economy

Blockchain architectures have emerged as a disruptive technology with the potential to significantly impact the digital economy and generate opportunities in various sectors [60,61]. This discussion explores how these architectures can be applied in the digital economy and what opportunities they offer based on contributions from experts in the field:

(1) Transformation of the financial industry: The authors of ref. [1] point out that blockchain architectures have transformed the financial sector by enabling fast and secure transactions without intermediaries. As the first blockchain-based cryptocurrency, Bitcoin has challenged the traditional financial system by enabling the transfer of value directly from person to person [37,62].

(2) Supply chain digitization: In the opinion of the authors of reference [53], blockchain architectures have the potential to revolutionize the supply chain by providing complete and transparent visibility of all processes. This scenario can lead to greater efficiency, product authentication, and reduced supply chain fraud.

(3) Digital asset management: The authors of ref. [56] note that blockchain architectures allow asset tokenization, meaning physical and digital assets can be represented as

digital tokens. This opens up opportunities for investing in and trading digital assets, such as art, real estate, and more, in a more accessible and efficient way.

(4) Smart contracts and automation: Ref. [56] introduced the concept of smart contracts, self-executing programs that operate on a blockchain. These contracts offer opportunities to automate a wide range of processes, from legal agreements to complex business processes, which can save time and costs.

(5) Digital identity: Digital identity management is a growing field that benefits from blockchain architectures. Authors such as the authors of reference [53] suggest that blockchains can provide a more secure and user-controlled digital identity system by allowing people to control their identity information.

Applying blockchain architectures to the digital economy can improve digital transactions' security, efficiency, and transparency, driving more robust economic growth and greater trust in digital systems.

6. Challenges and Obstacles to Overcome

On continents such as Africa, various countries are exploring using blockchain technology to address the lack of access to financial services and transparent supply chain management in agriculture processes. The biggest challenge lies in their underdeveloped technological infrastructure and the various regulatory issues imposed by the government. Asia, for its part, has invested heavily in developing blockchain technologies, and different solutions have been implemented in important areas such as food traceability and digital payments. However, cultural and economic diversity and differences in regulation between countries are the most significant obstacles, without ignoring geopolitical competition, which also plays an important role.

In the European Union, blockchain initiatives have been supported in sectors such as energy and health, while individual countries have implemented solutions in supply chain and identity management. However, the biggest drawback presented in this part of the world is that cultural and business acceptance varies between European countries. In Oceania, Australia is the only country leading the adoption of Blockchain in areas such as property record management and supply chain. The main challenges encountered in this region are low population density and regulatory clarity.

On the other hand, in North America, private and government companies have been experimenting with Blockchain in areas such as health records management, supply chain, and payment efficiency. The biggest challenge presented is the existing competition and interoperability between various blockchain platforms [63]. Likewise, there is the inconvenience of addressing regulatory and privacy issues that still need to be resolved in private or public companies.

In South America, countries such as Chile and Brazil have seen the application of Blockchain in agricultural supply chain management and land ownership. These countries face both economic and infrastructure challenges.

Despite their advantages and promises, Blockchain architectures face a series of challenges and obstacles in their application in the digital economy, as various experts in the field have noted [64,65].

One of the key challenges highlighted by authors such as the authors of reference [54] is scalability in public blockchains. As the number of users and transactions on a blockchain network increases, the speed and cost of operation can become problematic. Solving this problem is critical in enabling blockchains to be efficient in large-scale digital economy environments.

Another challenge raised by the same author is the need for standards and the difficulty in achieving interoperability between different blockchains; the digital economy requires blockchains to communicate effectively and this lack of standardization can hinder integration [66,67].

Likewise, ref. [54] emphasizes that more understanding and knowledge about blockchains can be a significant obstacle, since education and promotion are essential to drive the adoption of this technology in the digital economy.

On the other hand, there is energy consumption, as noted by the authors of reference [1], especially in blockchains based on proof of work (PoW), such as Bitcoin. The energy required to maintain grid security raises environmental concerns about long-term sustainability. Furthermore, according to these authors, the high initial cost of development and configuration, especially for companies, can be an obstacle to adoption.

As blockchain technology advances, there is also a significant environmental impact that deserves attention due to the growing popularity of specific cryptocurrencies, such as Bitcoin, raising concerns about the energy consumption associated with the cryptocurrency mining process, which involves multiple nodes validating and recording transactions, for which a high-powered infrastructure is needed with hardware that is as up-to-date as possible and very efficient in terms of performance in order to solve complex calculations, which, in turn, requires a powerful cooling system [68]. The high complexity generated by producing cryptocurrencies results in the need to use a large amount of electricity, directly affecting the environment and the traditional electrical ecosystem and contributing to the global carbon footprint.

The environmental dilemma intensifies when it is considered that many cryptocurrency mining operations occur in regions where electricity is primarily generated from fossil fuels. Dependence on these non-renewable energy sources further exacerbates concerns about the environmental sustainability of blockchain technology [69].

However, it is essential to recognize that blockchain technology contributes positively to the environment. Some projects seek to develop solutions that minimize the environmental impact of cryptocurrency mining, promoting the use of renewable energy and energy efficiency.

Concerns about data privacy and regulations, as mentioned by the authors of reference [53], are also significant challenges. Despite the inherent transparency of blockchains, it is essential to address the need for privacy in certain contexts and navigate varying regulations worldwide.

Finally, cybersecurity is an important aspect, as the authors of reference [54] point out. Although blockchain technology is secure, malicious actors can look for weaknesses in the blockchain ecosystem to exploit.

These challenges and obstacles represent critical areas that must be addressed so that blockchain architectures can realize their full potential in the digital economy [70].

7. Relevant Case Studies

In the digital economy, various blockchain architectures are being used in specific applications, and below are some concrete examples of how blockchain technology is being used in the digital economy:

(1) Cross-Border Payments and Transfers: Companies like Ripple use blockchain technology to facilitate faster and cheaper international payments. This is especially useful in global e-commerce and remittances.
(2) Cryptocurrencies: Cryptocurrencies like Bitcoin and Ethereum are critical examples of how blockchain is used as digital money. Users can make online purchases, investments, and value transfers without intermediaries.
(3) Decentralized Finance (DeFi): DeFi platforms such as Aave, Compound, and MakerDAO use blockchain-based smart contracts to offer decentralized financial services, such as loans, exchanges, and interest generation.
(4) Asset Tokenization: Blockchain is used to tokenize physical assets, such as real estate and art. This allows investors to buy fractions of expensive assets and trade them online.
(5) Secure Electronic Voting: Some countries and organizations have explored blockchain-based electronic voting to improve security and transparency in elections.

(6) Digital Identity Management: Blockchain ensures the security of people's digital identity. Users can control their personal information and share only necessary information online.
(7) Product Authentication: In the luxury goods industry, blockchains are used to authenticate the authenticity of products, which helps prevent counterfeiting.
(8) Transparent Supply Chains: Large companies, like Walmart, track products throughout their supply chains using blockchains. This provides transparency and a faster response to quality or safety issues.
(9) Online Games and Digital Collectibles: Some online games use blockchains to allow the ownership and trading of in-game objects and characters as digital assets.
(10) Internet of Things (IoT): Blockchain is used in IoT applications to ensure secure communication and transactions between connected devices, such as smart meters and industrial sensors.

The examples above demonstrate how the blockchain has become a versatile technology with numerous applications in the digital economy, from finance and e-commerce to product authentication and identity management. Its ability to provide security, transparency, and efficiency makes it an attractive solution in various sectors. Below are some specific applications of Blockchain in the Digital Economy:

Bitcoin (Public Blockchain):

- Transfer of Value: Bitcoin is the most well-known cryptocurrency and is used to transfer value online without the need for intermediaries. People can buy goods and services online, invest, and transfer funds globally.

Ethereum (Public Blockchain):

- Smart Contracts: Ethereum allows the creation and execution of smart contracts, which are self-executing programs that automate agreements and transactions. They are used in various applications, from decentralized finance (DeFi) to online gaming and electronic voting.

Hyperledger Fabric (Consortium Blockchain):

- Supply Chain Management: Companies like IBM use Hyperledger Fabric to track and verify the product supply chain, increasing transparency and reducing fraud.

Corda (Consortium Blockchain):

- Financial markets: Corda is used in financial market applications, where financial assets can be traded and settled more efficiently and securely.

Quorum (Consortium Blockchain):

- Banking and Finance: Quorum has been used in banking applications, including cross-border payments and bond issuance.

Binance Smart Chain (BSC, Public Blockchain):

- Decentralized Finance (DeFi): BSC has become a popular platform for DeFi applications, including decentralized exchanges, lending, and cryptocurrency staking.

Cardano (Public Blockchain):

- Education and Electronic Voting: Cardano has been used to create electronic voting systems and provide verifiable academic certifications.

Algorand (Public Blockchain):

- Asset Tokenization: Algorand has been used to tokenize physical and digital assets, such as real estate and art.

VeChain (Public and Consortium Blockchain):

- Authentication and Traceability: VeChain is used in product authentication and tracking applications, such as luxury product authenticity and food traceability.

IOTA (Tangle, a blockchain-like technology):

- Internet of Things (IoT): IOTA focuses on the machine economy and facilitates transactions and communication between IoT devices [71].

8. Perspectives and Future of Blockchain Architectures

The future of blockchain architecture in the digital economy is promising and full of opportunities. As this technology continues to evolve, key developments are likely to be seen. One of the current challenges of public blockchains is their ability to scale and handle large numbers of transactions. In the future, solutions will likely be implemented for greater performance and scalability without compromising security [72,73].

As blockchains become more user-friendly and integrated into everyday applications and services, greater adoption will be seen in both the consumer and enterprise arenas. This could include everyday blockchain-based payment systems and secure voting applications.

Likewise, we will see greater tokenization of traditional assets, such as real estate, stocks, and bonds. This will allow investors to buy and trade a wide range of assets more accessible and efficiently. This will lead to a more inclusive and accessible economy.

Developing interoperable standards between different blockchains will gain prominence, allowing for more fluid collaboration between platforms. This interoperability will facilitate the creation of end-to-end solutions and foster innovation [74,75].

The convergence of technologies will lead to more intelligent and efficient systems. Predictions suggest that, in this technological union, the digital economy will experience a paradigmatic change, fostering a future where decentralization and transparency are the essential pillars of economic progress. Regulatory frameworks are also expected to adapt to encompass the technology as governments and institutions seek to balance innovation with consumer protection and financial stability. A panorama is outlined where traceability and trust are intertwined.

With the growing awareness around sustainability, the tokenization of assets, and the push for smart contracts, Blockchain stands as a catalyst for creating efficient and environmentally friendly systems. The decentralization of finance is seen as an unstoppable trend, challenging traditional models and democratizing access to financial services around the world [76].

However, education emerges as the fundamental compass for this technological revolution, and a solid knowledge base is needed that ranges from the basics of blockchain technology to a deep understanding of its applicability in various sectors [77]. Educational programs should prioritize practical learning, allowing students to interact directly with the creation and management of smart contracts and explore real use cases. Training in technical skills is crucial, but education must go further, cultivating the ability to think critically about the ethical, social, and economic impacts of Blockchain. Creativity and problem-solving should be encouraged, preparing students to adapt to a constantly changing business environment.

Collaboration between educational institutions, industry, and blockchain projects is essential, where bridges can be established that allow students to participate in real projects and obtain practical experience, which would strengthen their preparation for the digital economy without having the experience of the connection with experts in the field and participation in technological communities, and aim to keep learners updated in a dynamic technological landscape.

Blockchain is expected to continue playing an important role in improving efficiency and transparency in supply chain management and logistics; the development and adoption of DApps is also expected to continue to grow in areas such as gaming, finance, and social media, giving users greater control over their data and assets [78,79].

The blockchain community will continue to innovate and develop new technologies and standards. This could include security, energy efficiency, and smart contract programmability advances.

9. Ethical and Safety Considerations

The ethical implications of blockchain architectures in the digital economy are a topic of growing interest and debate in the academic and professional community. Blockchains are transparent by nature, meaning that all transactions are visible to network participants. This can raise ethical privacy concerns, especially in applications that involve personal or financial data. People have the right to privacy, and blockchain solutions must address these concerns by implementing appropriate measures to protect sensitive data. The inherent transparency of blockchains, which allows visibility of all transactions, raises ethical privacy concerns. As David Birch points out in his book *Before Babylon*, *Beyond Bitcoin* [80], a balance between the transparency necessary for trust and user privacy must be found.

Permanent data storage or the immutability of data on the blockchain means that recorded information cannot be easily deleted or modified. This can be problematic if incorrect or harmful data are recorded. Ethics dictate that mechanisms must be established to correct errors and remove harmful information without compromising the integrity of the blockchain.

Regarding smart contracts, they are understood to be self-executing computer programs that operate on the blockchain; but if a smart contract has a bug or performs harmful actions, who is responsible? Establishing responsibility and ethics in the creation and execution of smart contracts is a significant challenge. Self-executing smart contracts can be misleading or contain errors. Nick Szabo, who coined the term "smart contract" in the 1990s, highlights the importance of clarity and security in smart contract programming to avoid unethical outcomes.

Blockchain-based applications must be equitable and accessible to everyone, regardless of geographic location or technical skill level. Digital exclusion is an ethical concern that needs to be addressed, and several academics, such as Primavera De Filippi and Aaron Wright, in their book *Blockchain and the Law* [81], highlight the need to ensure that blockchains are accessible to everyone.

Ethical considerations emerge in the digital economy permeated by Blockchain that outline the intersection between technological innovation and social responsibility [82,83]. First, the decentralization inherent in blockchain technology can have two functions: while it provides financial empowerment to marginalized communities, it also poses ethical challenges in terms of privacy and data management, demanding a delicate balance between the transparency desired and the protection of sensitive information; concerning cryptocurrencies, questions are raised about financial stability and equity of access, and the need to address financial inclusion ethically is highlighted as a moral imperative in the development and adoption of emerging financial technologies [84,85]. The lack of clear regulations can lead to fragmentation and inequality, where those with greater technical capacity and resources benefit at the expense of the less privileged. At a deeper level, automation through smart contracts raises ethical questions about responsibility and decision-making. How are errors or biases managed in the codes? How is efficiency balanced with the human oversight necessary for ethically sound decisions?

The emergence of the digital economy driven by Blockchain represents a technological revolution and entails profound social impacts that reconfigure economic and social structures. Firstly, the decentralization inherent in blockchain technology has the potential to empower marginalized communities, providing them with direct access to financial services and eliminating barriers that have historically perpetuated economic exclusion. This change translates into a decrease in inequality, as peer-to-peer transactions and smart contracts allow people to actively participate in the economy without relying on costly intermediaries. Automating processes through smart contracts can also free up time and resources, allowing people to focus on more creative and meaningful activities. Education becomes a fundamental element to fully take advantage of the opportunities of the digital economy applied to blockchain technology, ensuring that communities can participate and benefit from this change [86–88].

(PoW)-based blockchains consume large amounts of energy. This raises ethical concerns about the environmental impact and sustainability of the technology. Exploring greener solutions, such as proof-of-stake (PoS)-based blockchains, is an important ethical consideration. In an *IEEE Spectrum* article, Morgan Peck points out ethical concerns about environmental impact and the need to consider more sustainable alternatives.

10. Conclusions

(1) Recent trends and developments in blockchain architectures drive their adoption in various sectors and applications. These advances address key challenges, such as scalability and interoperability, while driving new business and smart contracts. The continued evolution of blockchain technology is critical to its role in the digital economy and the transformation of numerous industries.

(2) Blockchain architectures represent a disruptive innovation that significantly impacts the digital economy. As these technologies continue to evolve, exciting opportunities present themselves for a variety of sectors, from finance to logistics to healthcare. The most recent trends in blockchain architectures reflect their growing adoption and ability to address challenges in the digital economy.

(3) Blockchain architectures open new perspectives in the digital economy by offering innovative and secure solutions in various sectors. Experts in the field have identified these opportunities and are exploring how to make the most of this technology to drive growth and efficiency in the digital economy.

(4) The application of blockchain technology in the digital economy has proven to be a promising solution for creating immutable records, securing transactions, and eliminating costly intermediaries. Concrete examples, such as transparent supply chains and asset tokenization, illustrate how these architectures can generate efficiency and trust in various sectors.

(5) Educating society about the digital economy powered by Blockchain is of utmost importance in the current and future context, as it provides people with the knowledge necessary to understand and take advantage of the opportunities offered by blockchain technology; a lack of understanding can result in distrust and resistance towards these innovations, while a solid education paves the way for informed adoption and active participation, not only concerning technical guidance but also concerning understanding of the social, ethical, and economic implications. In [1], the authors argue that education and deep understanding of applied blockchain technology are essential to unlock its true transformative potential in the economy. Society must appreciate how decentralization and transparency can improve efficiency and reduce corruption in different sectors. In [53], it is pointed out that transparency of transactions on the blockchain can limit opportunities for corruption. Exploring Blockchain and the digital economy requires a multifaceted approach that includes continuing education, active community involvement, and a balanced understanding of the technical and ethical aspects.

(6) The intersection between the digital economy and blockchain technology outlines a future of unprecedented innovation, decentralization, and efficiency. Blockchain is transforming how we handle financial transactions and redefining how we think about trust, security, and collaboration in the digital age. Authors such as the authors of reference [77] argue that the digital economy is undergoing a revolution driven by the adoption of digital assets that serve as a means to establish a form of money resistant to inflation and government manipulation. This vision suggests that the blockchain-based digital economy is innovating in business efficiency and challenging established paradigms around the financial system and asset management. The blockchain-powered digital economy presents significant opportunities, from the tokenization of assets to the decentralization of finance and the creation of smart contracts. However, this shift has challenges, such as ethical issues, regulatory considerations, and the need for widespread education.

(7) Ultimately, the future of blockchain architectures in the digital economy looks promising, potentially transforming business processes and providing new opportunities. An informed and ethical adoption of this technology will be vital to maximizing its benefits and overcoming the challenges that arise along the way. As advances and research in this field continue, it is important to stay up-to-date and be prepared to adapt to an ever-changing environment.

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