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Blockchain in Space Exploration

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ABSTRACT

Blockchain, the backbone of cryptocurrencies like Bitcoin, is a distributed ledger technology, in which blocks of data are chained together by cryptographic hashing. It operates on a decentralized network of computers, ensuring transparency, security, and immutability of data. Integrating blockchain in space operations introduces decentralized systems, reducing reliance on a central authority. Blockchain can serve as one of the potential technology solutions to help remediate some of the challenges confronting space exploration. In this paper, we embark on a journey to unravel the implications of marrying blockchain technology with space concepts.

KEYWORDS: *blockchain, space exploration, space colonization, aerospace*

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INTRODUCTION

Recently, modern technologies have aided business titans in deciding to use digital currency rather than conventional trade in order to avoid fraud. Blockchain enables the existence of Bitcoin and many other cryptocurrencies. A cryptocurrency refers to a digital asset that works as a medium of exchange between various business organizations. Figure 1 shows the symbol of blockchain [1].

The evolution of human interest in space has been driven by the desire to explore the unknown, pushing the boundaries of knowledge with the urge to discover new worlds. Starting with the curiosity about the sky, moon, sun, and other stars visible to human eye, we have seen the first human to walk on the moon, as typically shown in Figure 2 [2]. This can be referred to as moving from Space1.0 to Space 2.0. The permanent presence in space with the International Space Station was the benchmark for the evolution from Space 2.0 to Space 3.0. Today we are in the middle of a full-scale evolution of the space sector into a new era, namely Space 4.0 [3]. Blockchain technology has transcended its financial origins to find applications in various industries, including space industry. It is an ideal candidate for revolutionizing the space exploration. It can enhance the security of space infrastructure.

WHAT IS BLOCKCHAIN?

Blockchain, a type of distributed digital ledger technology (DLT), is a relatively new and exciting way of recording transactions in the digital age. It is a decentralized and distributed digital ledger technology that securely records and verifies transactions across multiple computers or nodes in a network. Basically, it is a chain of blocks in which each block contains a list of transactions. The blockchain technology was created as the foundational basis for Bitcoin – a digital currency in which secure peer-to-peer transactions occur over the Internet. It is expected that the spending on blockchain solutions worldwide would grow from 4.5 billion USD (2020) to an estimated value of 19 billion USD by 2024 [4].

Originally developed as the accounting method for the virtual currency Bitcoin, Blockchains are appearing in a variety of commercial applications today. Blockchain technology is a type of distributed

digital ledger that uses encryption to make entries permanent and tamper-proof and can be programmed to record financial transactions. It is used for secure transfer of money, assets, and information via a computer network such as the Internet without requiring a third-party intermediary. It is now being adopted across financial and non-financial sectors. As a catalyst for change, the Blockchain technology is going to change the business world and financial matters in major ways.

The first Blockchain was conceived in 2008 by an anonymous person or group known as Satoshi Nakamoto, who published a white paper introducing the concept of a peer-to-peer electronic cash system he called Bitcoin [5,6]. Bitcoin and Ethereum are the first two mainstream blockchains. Other modern blockchains include Namecoin, Peercoin, Ether, and Litecoin. Figure 3 shows different components of blockchain [7].

Blockchain combines existing technologies such as distributed digital ledgers, encryption, immutable records management, asset tokenization and decentralized governance to capture and record information that participants in a network need to interact and transact. As illustrated in Figure 4, a complete blockchain incorporates all the following five elements [8]:

- *Distribution:* Digital assets are distributed, not copied or transferred. A protocol establishes a set of rules in the form of distributed mathematical computations that ensures the integrity of the data exchanged among a large number of computing devises without going though a trusted third party. A centralized architecture presents several issues including a single point of failure and problems of scalability.
- *Encryption:* BC uses technologies such as public and private keys to record data securely and semi-anonymously. Completed transactions are cryptographically signed, time-stamped, and sequentially added to the ledger.
- *Immutability:* The Blockchain was designed so these transactions are immutable, i.e. they cannot be deleted. No entity can modify the transaction records. Thus, Blockchains are secure and meddle-free by design. Data can be distributed, but not copied.
- *Tokenization:* Value is exchanged in the form of tokens, which can represent a wide variety of asset types, including monetary assets, units of data or user identities.
- *Decentralization*: No single entity controls a majority of the nodes or dictates the rules. A consensus mechanism verifies and approves transactions, eliminating the need for a central intermediary to govern the network.

Bitcoin and its underlying blockchain technology increasingly impact all facets of society. Bitcoin's status as digital gold is merely the tip of this technology. Figure 5 shows Bitcoin [9]. Although blockchain technology will for all time be associated with Bitcoin due to their common genesis, it has broader applications. Cryptocurrency will increasingly become a factor in family law issues as well.

BLOCK CHAIN IN SPACE EXPLORATION

Space exploration has come a long way since the first moon landing in 1969. The space industry has been experiencing an unprecedented surge in recent years and is expected to continue to grow. It is currently undergoing rapid evolution as private companies or other entities transform the sector and spearhead innovation in space technologies.

Spacecraft and satellites require a secure data communication network. Satellites present an interesting opportunity on which to build a blockchain network that would enable a decentralized flow of data between machines. A conceptual view of a blockchain network is presented in Figure 6 [10].

The rise of blockchain technology has transformed how we conduct transactions and share information online. National Institute of Standards and Technology Blockchain, or the more general term, distributed ledger technology (DLT), is gaining traction across various industries outside the space sector. NASA has embraced blockchain technology in various projects, including secure communication protocols and tracking the procurement of space equipment. It is looking to use smart contracts on the Ethereum blockchain in the agency's SensorWeb program. The main objective of the program is to create an interoperable environment for a diverse set of satellite sensors via the use of software and the Internet.

APPLICATION OF BLOCK CHAIN IN SPACE EXPLORATION

Blockchain technology is so new that it seem difficult to see direct applications in space exploration. One example of blockchain in space is AstroChain, which provides a platform for space enthusiasts to share astronomy content and images. While the most popular use of cryptocurrency has been in the financial sector, it has been applied for space. Other applications of blockchain in space include the following [11-14]:

- *Space Economy:* The space economy has evolved significantly from its initial focus on government-

funded projects to a vibrant ecosystem involving private companies, international collaborations, and a surge in commercial space activities. Blockchain technology has the potential to revolutionize the space economy by introducing greater transparency, efficiency, and accessibility to space-related activities, fostering a new era of collaboration and innovation in the cosmic frontier. It has the potential to significantly disrupt and enhance the space economy by providing a secure, transparent, and decentralized system for managing assets, tracking data, and facilitating transactions across various space operations.

- *Space Debris:* This is a growing challenge that threatens the future of space exploration and satellite operations. As the number of satellites and space missions increases, so does the accumulation of debris, posing risks to spacecraft, satellites, and even the International Space Station (ISS). Addressing this issue requires innovative solutions, and blockchain technology emerges as a promising tool to enhance space debris management and promote sustainable space exploration. Blockchain can enhance space debris tracking efforts by providing a means for real-time open source data sharing on space debris, while developing new incentive mechanisms to promote sustainable space exploration. One of the primary applications of blockchain in space debris management is the creation of a decentralized database for tracking and identifying debris. Blockchain's smart contracts offer an automated mechanism for executing agreements related to space debris removal. The integration of blockchain technology into space debris management represents a significant step toward ensuring the long-term sustainability of space exploration. Figure 7 shows some space debris [11].
- *Supply Chain Management*: Another area where blockchain is revolutionizing space exploration is supply chain management. Managing the supply chain in space is a complex process. Blockchain technology can streamline the supply chain by creating a transparent and immutable record of each transaction. This will help to reduce errors, delays, and inefficiencies, making the supply chain more cost-effective and reliable. Blockchain technology can support the development of space-based supply chain management systems. Space infrastructure requires a constant flow of resources and materials, and blockchain can provide a secure, transparent platform for tracking the movement of goods and ensuring supply chain efficiency. Blockchain can enhance the supply chain management of recycling materials, ensuring the traceability and authenticity of recycled components. This not only supports the circular economy within the aerospace industry but also promotes the responsible use of resources in space manufacturing. Supply chain logistics are challenging when dealing with space, given the vast distances and communication lags involved.
- *Earth Observation:* Another growing industry that has significant growth potential involves Earth Observation. This is an evolving sector that involves using remote sensing technologies to collect information on the planet's physical, chemical, and biological systems and to monitor land, water (i.e., seas, rivers, lakes), as well as the atmosphere. Once analyzed, information collected through earth observation can be assimilated into detailed models to produce information and intelligence Space-based geographical applications and earth observation data are highly multidimensional with coordinates, timestamps, different data from different sensors, data from different suppliers with different revenue schemes. Eventually everyone can access space data, not only governments, intelligence agencies or big corporates. Blockchain can assure satellite data is accessed by everyone in a trusted manner as the authenticity and the integrity of data will be assured in a distributed ownership infrastructure.
- *Satellite Communication:* Satellite communication is vital to the global telecommunications network, enabling essential services - calls, internet access, TV broadcasting, and radio channels. In a standard satellite communication link, a signal is transmitted or uplinked from our planet to a designated place - a station. Traditional satellite networks rely on centralized infrastructure and control systems, leading to single points of failure and vulnerabilities. A typical satellite communication system is shown in Figure 8 [12]. Blockchain technology can be used in satellite communication to enhance data security, transparency, and integrity by creating a decentralized and immutable ledger for storing satellite data. Decentralized satellite networks enhance resilience, security, and efficiency, enabling global connectivity, remote sensing, and satellite-based services. The integration of blockchain technology with satellite communication heralds a new era of possibilities. Blockchain technology gives the possibility to establish a decentralized communication network that boasts enhanced protection when dealing

with cyber risks. It could track a satellite's movement, sharing data with all suppliers, and can enforce rules such as any changes made to the satellite require the consensus of the team. Figure 9 shows the integration of blockchain technology and satellite communications [13].

- *Space Colonization:* In recent years, humanity's gaze has shifted from our earthly confines to the vast expanse of space. This new era of exploration is driven by a collective ambition to transcend our planetary boundaries and establish a human presence among the stars. The ultimate target in this space race is Mars — a planet that has long captivated our imagination. With robotics like the Mars Rover already providing invaluable data from the Martian surface, the dream of human colonization feels closer than ever. Blockchain technology can potentially propel humanity towards Mars colonization by providing a transparent, secure, and decentralized system for managing crucial aspects of a Martian colony, including resource allocation, property ownership, governance, and even the tracking of vital supplies. It can play a significant role in enabling a more efficient, transparent, and equitable Martian colony by managing resources, property ownership, governance, and economic transactions in a decentralized manner. Companies like SpaceX, Blue Origin, and NASA have been at the forefront of this cosmic endeavor, pushing the limits of technology and human ingenuity to realize this celestial ambition. MarsVerse is the world's first metaverse ecosystem with Web3 interstellar colonization at its core. It recruits Mars colonization volunteers globally through Avatars to help humanity officially enter the universe.

BENEFITS

Integrating blockchain technology in space operations introduces decentralized systems, reducing reliance on a central authority. Blockchain can be used in space exploration to enhance security, transparency, and trust in many ways. Establishing trust in decentralized space systems involves demonstrating the reliability, security, and efficiency of blockchain applications. Space-based blockchain can provide a fully decentralized and sovereignty agnostic infrastructure. Blockchain technology presents a unique opportunity to enhance space communications, offering a more secure, efficient, and accessible infrastructure Other benefits include [9,15]:

- *Security:* This is paramount in space missions. Blockchain's cryptographic algorithms provide robust security, protecting sensitive data from potential cyber threats. As space missions involve confidential information and critical communication, blockchain acts as a shield against unauthorized access and tampering. Blockchain's cryptographic principles offer a robust solution to enhance the security of satellite communication.
- *Improved Transparency:* Transparency is a cornerstone in space-related transactions, especially in collaborations involving multiple entities. Blockchain's transparent and traceable nature ensures that every transaction is recorded and accessible, fostering trust among stakeholders.
- *Smart Contracts:* Smart contracts, a key feature of blockchain, can automate and enforce agreements between satellite operators, ground stations, and other service providers. They are self-executing contracts coded into the blockchain that automatically perform actions once predefined conditions are met. They streamline processes in the space economy. They automate data transactions and enforce data sharing agreements. Automating tasks like satellite launches, resource allocation, and data sharing through smart contracts reduces operational costs and minimizes the risk of human error. A smart contract is constrained by the boundaries of the database in which the smart contract resides.
- *Space Tourism:* The burgeoning space tourism industry can leverage blockchain for secure transactions, identity verification, and customer data protection. This synergy enhances the overall experience for space tourists while addressing privacy concerns.
- *Centralized Systems:* Current data management systems rely heavily on centralized servers on earth, leading to risks of single points of failure and inefficiencies in data handling. Blockchain's decentralized nature offers an innovative solution to these challenges.
- *Interplanetary Communication:* As humanity prepares for interplanetary missions, the need for secure and reliable communication will become more pressing. Blockchain could help create an "interplanetary Internet," enabling decentralized, secure, and tamper-proof communication between Earth, Mars, the Moon, and beyond.

CHALLENGES

The space industry faces numerous challenges ranging from data management to resource allocation. Foundational technologies like blockchain must first

overcome technological, organizational, regulatory, and political barriers. Other challenges include [8,14]:

- *Security:* Although blockchain enhances security, implementing it in space introduces unique challenges. Robust solutions involving space-hardened hardware and continuous monitoring are crucial to mitigate these challenges.
- *Regulation:* The integration of blockchain in space operations raises regulatory concerns. Establishing clear regulatory frameworks to govern space-based blockchain activities is essential. Since governments play a pivotal role in shaping the future of blockchain in space, collaborative efforts between governments and space agencies are essential to create a regulatory framework. The development of standards and regulations for blockchain use in the space industry is still evolving.
- *Collaboration:* Collaborations between technology and aerospace industries foster innovation. Partnerships can lead to the development of integrated solutions that address the unique challenges of space while advancing blockchain technology. Blockchain technology enables collaboration without compromising sensitive information, enhancing joint efforts in debris monitoring, threat assessment, and the development of comprehensive mitigation strategies.
- *Sustainability:* As space activities increase, environmental sustainability becomes paramount. Implementing eco-friendly practices in space exploration, supported by blockchain technology, can minimize the ecological footprint of space missions. The potential for recycling materials recovered from space debris presents an opportunity for sustainability in space operations.
- *Harsh Environments:* Harsh space conditions can impact data integrity. Employing advanced encryption methods and developing space-hardened blockchain solutions are imperative to safeguard the reliability of data in space-based applications.
- *Complexity:* Integrating blockchain technology with existing space systems requires sophisticated development and adaptation. Blockchain for space systems may offer compelling advantages by reducing complexity across a range of business, operational, and security applications. NASA as well as many other businesses may still need to integrate with older technology. Another layer of complexity is added when we take into account the possibility of fractional ownership.
- *Memory Constraints:* One of the challenges in working with devices is the memory constraints. This is amplified on a satellite because much of the memory is reserved as a backup for the satellite itself. So we need to creative to be able to generate the private keys for new accounts.
- *Cost:* One of the main challenges that have always slowed down any attempt by humanity to research the cosmos involves acquiring the funds necessary to leave earth's orbit. Recently, space was only allowed to governments or space agencies due to extremely high costs and operational risks which made space exploration inaccessible to private companies. Thanks to the advanced satellite, launch, or other space technologies, we now witness the emergence of other players in space exploration, colonization, and commercialization. Recently, SpaceX launches Starlink LEO satellites, as an example of such a new entrepreneurial spirit that is rapidly shaping a new space economy.
- *Data Management:* Space missions generate vast amounts of data, including telemetry data, sensor readings, and imagery, which must be managed, analyzed, and shared efficiently. For example, NASA's Mars Rover missions produce hundreds of gigabytes of data that are transmitted back to earth. This data needs to be securely stored, shared, and analyzed, often in real time. Blockchain-based solutions provide secure, transparent, and immutable data management for space missions, ensuring data integrity, provenance, and traceability.
- *Scalability:* Current blockchain technology faces limitations in handling large volumes of data transactions, a critical factor for space communication. Integrating blockchain with large-scale satellite networks may pose scalability challenges due to the computational demands of consensus mechanisms.
- *Latency:* The inherent latency associated with blockchain transactions could pose a challenge for real-time space communication applications. Depending on the network architecture, latency in satellite communication could impact blockchain transaction speeds

CONCLUSION

Blockchain is an emerging technology that is on the verge of transforming many industries, and space exploration is no exception. The growing interest in blockchain development for space applications indicates that it could very well be the future of space missions. As humanity ventures further into the

cosmos, blockchain may become as integral to space exploration as rockets and rovers. As the industry continues to grow, blockchain technology is poised to play an increasingly important role in shaping the space industry's future. As blockchain moves into outer space, its ability to tokenize spacecraft and payloads is key to its success. Its ability to provide decentralized, secure, and efficient data management solutions is a game-changer for future space missions. More information on the integration of blockchain technology into space exploration is available from the books in [16,17].

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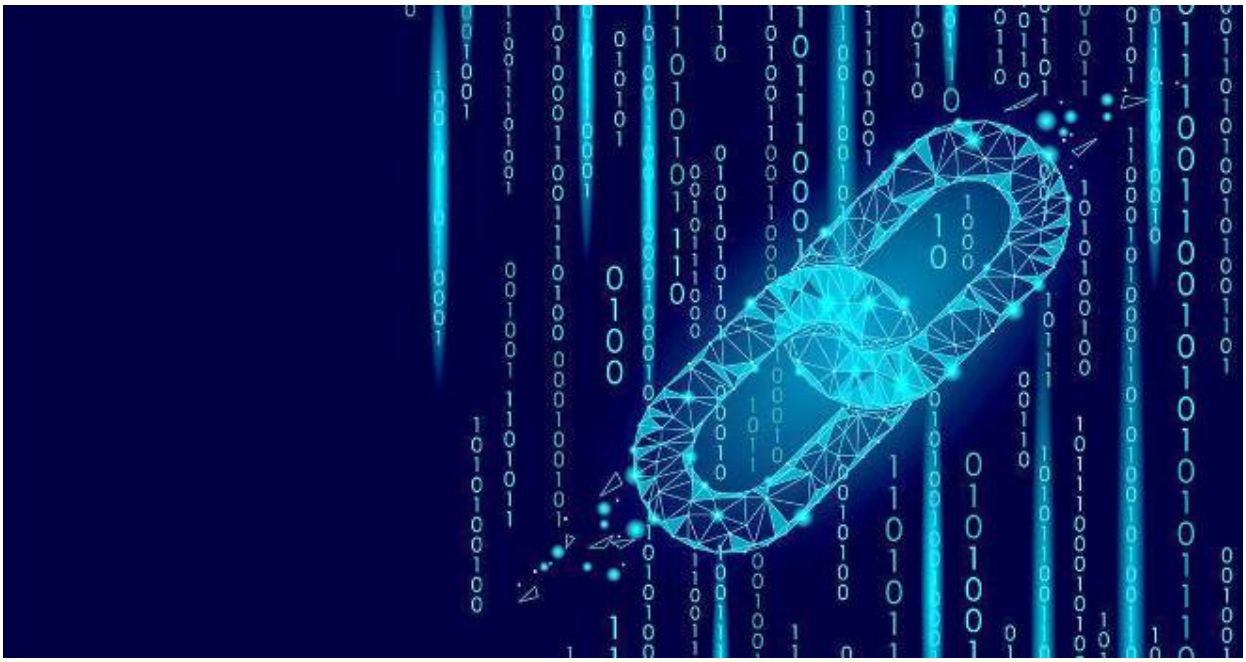

Figure 1 The symbol of blockchain [1].

Figure 2 An astronaut [2].

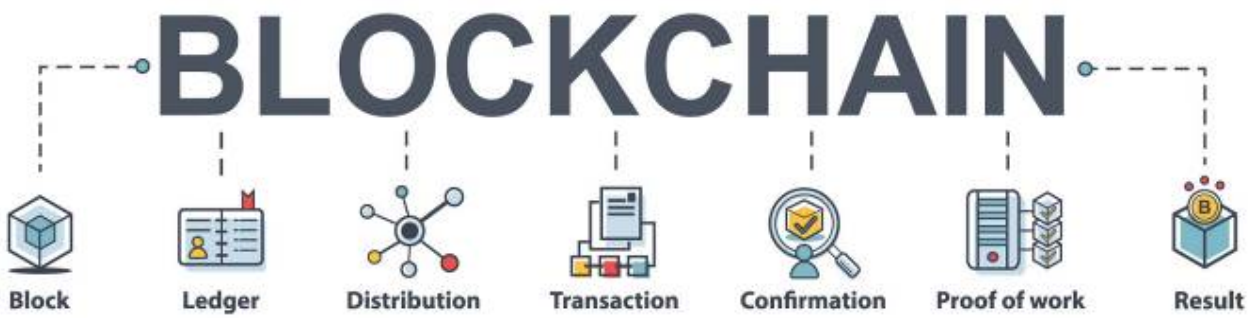

Figure 3 Different components of Blockchain [7].

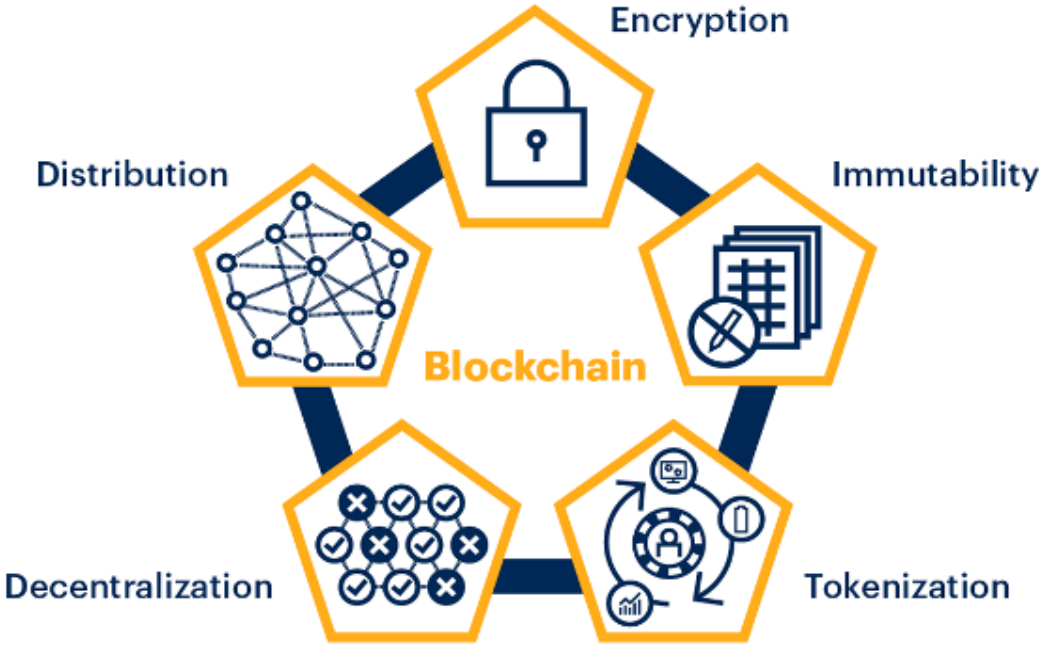

Figure 4 Five key elements of Blockchain [8].

Figure 5 Bitcoin [9].

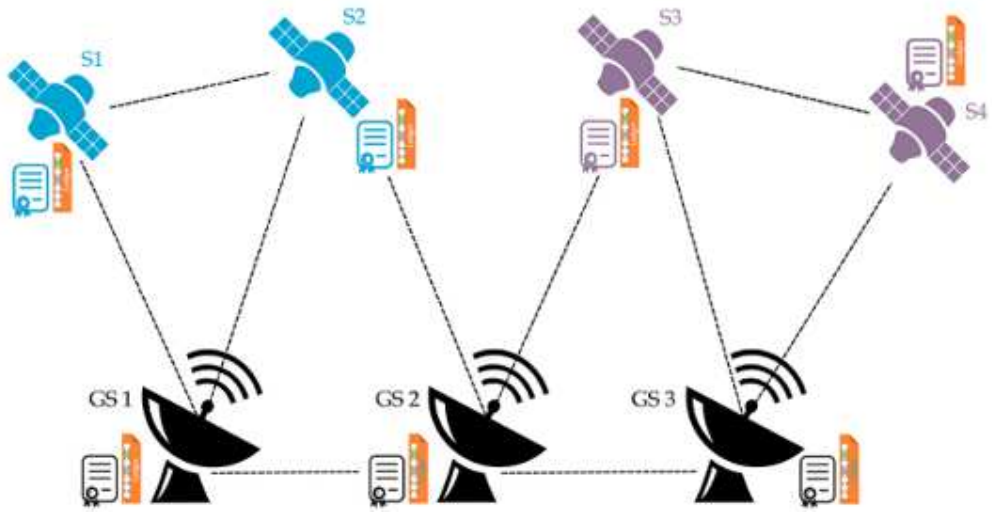

Figure 6 A conceptual view of a blockchain network [10].

Figure 7 Some space debris [11].

Figure 8 A typical satellite communication system [12].

Figure 9 Integration of blockchain technology and satellite communications [13].