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Interplanetary CubeSat Networks: Challenges and Future Prospects in Deep Space Communication

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Abstract: The rapid development of miniaturized space technology has enabled CubeSats to extend their reach beyond low Earth orbit and be used for interplanetary missions. These small, low-cost spacecrafts hold new promises for distributed science observations, communication relay, and autonomous exploration. Establishing dependable communication networks for CubeSats in deep space is a significant challenge due to severe latency, limited power budgets, low bandwidth, and the lack of specialized interplanetary infrastructure. This review addresses the fundamental communication challenges of interplanetary CubeSats, including signal loss over large distances, Doppler shift, and frequency stability. It also speaks of current and future solutions such as Delay/Disruption Tolerant Networking (DTN), optical communications systems, and cooperative CubeSat swarm development. Through current mission analysis and projected architecture, this paper highlights the technological advances needed to enable scalable and fault-tolerant interplanetary CubeSat networks. The review is completed with a summary of future research directions and the urgent necessity of autonomous, adaptive communication systems to facilitate the next generation of deep space exploration.

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1. Introduction

CubeSats have transformed space exploration by providing a small, affordable, and modular platform for a range of missions, from Earth observation to scientific experimentation in low Earth orbit (LEO). Originally conceived as educational vehicles, CubeSats have evolved into useful scientific instruments and are now being evaluated for more advanced interplanetary missions. Their short development cycle and low cost make them the best candidates for deep space missions, where sending large spacecraft can be economically or logistically infeasible. As missions go farther than Earth orbit, the reliability of CubeSats to communicate over long distances becomes a stringent limitation. Deep space communication adds a new set of challenges that are not found in near-Earth missions, such as severe signal attenuation, high latency, low transmission power, and high bandwidth constraints. In contrast to the large spacecraft with high-gain antennas and robust transceivers, the CubeSats are significantly constrained by their size, power, and thermal management capabilities, so deep space communication is a non-trivial problem. This review paper highlights the fundamental communication challenges that CubeSats are faced with in interplanetary missions and describes the technological and architectural innovations for addressing them. It also investigates the possibility of networked CubeSat architectures like constellations and swarms in providing scalable, autonomous communication infrastructure for deep space exploration in the future. Through current development and creating research, this article aims to give a comprehensive understanding of how the future path towards effective and robust interplanetary CubeSat communication networks is made possible.

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2. Literature Review

The development of CubeSats from a science experiment to a scientifically validated platform has provided new avenues for interplanetary missions. Different studies have focused on the communication, capabilities, and limitations of CubeSats in deep space missions, laying grounds for future developments.

A detailed overview of the trends in satellite communications on the advent of the "New Space" paradigm and with a focus on deploying high-scale constellations to Low Earth Orbit (LEO) for improved latency and data throughput [1]. Although this research focuses on LEO systems, it provides insights as to how technologies like 5G integration, Non-Terrestrial Networks (NTNs), and Software-Defined Networking (SDN) could be implemented in shaping future deep space communication infrastructure. Quantum key distribution and machine learning are highlighted by the authors as the latest technologies that can be used to enhance security and flexibility in satellite communication systems, as well as those of interplanetary CubeSats. The history and integration of CP1, a pioneering CubeSat to be made at California Polytechnic State University [2]. Successful power management and communications are presented as being required in effective electronic systems by their work so that small satellites can perform their missions. While CP1 was operated in LEO, the low-cost and modularity design principles outlined in the paper also extend to interplanetary CubeSats, specifically scalable and robust communication subsystem design with constrained power and volume budgets.

Earth observation feasibility with CubeSats, grouping remote sensing technologies into types based on prospective deployment onto CubeSats. Although they refer to imaging payloads and science instruments, a reference to CubeSat constellations for increased spatial and temporal resolution in effect confirms interplanetary constellations of CubeSats [3]. Coordination, synchronization, and efficient data transfer from multiple spacecraft increasingly become the priorities in earth observation missions as well as in deep space missions. Three conceptual mission concepts for the use of CubeSats in expanding Mars exploration. They conclude that CubeSats, despite power and antenna limitations, could be of use for planetary science missions with long temporal observation and distributed measurement [4]. The missions would be heavily reliant on trustworthy communication links directly to the planet or in terms of relay by a connecting spacecraft. This article highlights the need for mission-specific communication techniques and demonstrates the scientific merit of CubeSat-based networks in interplanetary missions. While not specifically addressing deep space communications, the article [5] examines novel propulsion approaches for CubeSats and criticizes the draconian design compromises that result from volume, power, and mass limitations. While propulsion is beyond the scope of this review, the paper lends general support to the theme of miniaturization of subsystems and its consequences for communications hardware - specifically thermal management, antenna deployment, and distributing power among subsystems.

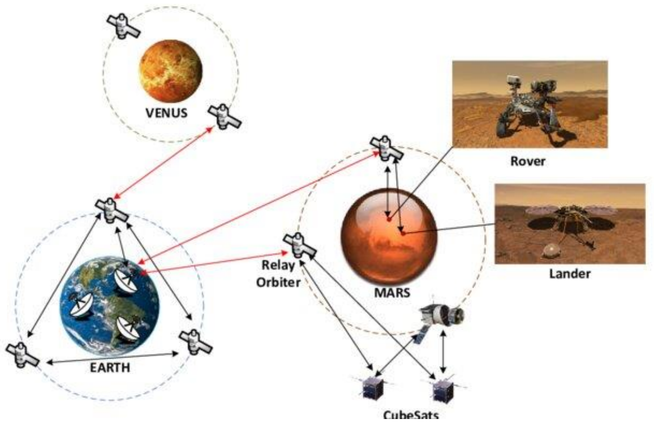

Figure-1 Relay-based design for CubeSat communication for interplanetary missions. [6]

Separately and together, these reports define the technical and potential challenges of employing CubeSats in interplanetary space. These reports acknowledge an imperative for light and nimble communication architectures that leverage technologies such as Delay/Disruption Tolerant Networking (DTN), optical communications, and autonomous data processing to transcend the deep space communication limitations.

3. Communication Architecture for Interplanetary CubeSats

Interplanetary CubeSat communication infrastructure must meet numerous challenges from deep space environments including vast distances, dense signal attenuation, and scarce onboard resources. Unlike Earth-orbiting CubeSats, which employ UHF/VHF bands and low-power omnidirectional antennas, deep space missions require more advanced communication systems that can connect to distant ground stations such as NASA's Deep Space Network (DSN). This calls for the use of higher frequency bands like S-band or X-band, as well as directional, deployable, high-gain antennas and more sophisticated transceivers, such as Software-Defined Radios (SDRs), to ensure compatibility and flexibility.

Integration with the DSN or comparable facilities is a critical aspect of interplanetary CubeSat design. Because of the stringent conditions for deep space communication, for example, precise frequency standards, modulation schemes, and signal timing - CubeSats must integrate into their hardware capability to meet these. The latencies and short DSN visibility windows require CubeSats to use a store-and-forward architecture, where the scientific and telemetry data are buffered onboard and is then transmitted during scheduled intervals of DSN visibility. This necessitates robust onboard data handling systems able to prioritize and process mission data autonomously.

To manage the extended delays and disconnects of deep space, most interplanetary missions employ Delay/Disruption Tolerant Networking (DTN). DTN is based on the "store-carry-forward" model, in which data packets are stored and relayed over opportunistic links and when they become available. Protocols such as the Bundle Protocol (BP) are designed specifically for this, to allow communication to continue even when continuous links are not present. DTN improves the reliability of interplanetary communication and must be used to facilitate distributed CubeSat constellations or swarms.

Autonomy is required for scheduling communication of deep space CubeSats. Since it will take some minutes, perhaps more, for signals to be transmitted from Earth to the CubeSat, there cannot be any real-time control. Thus, the CubeSat must make its own decisions, such as, when to communicate, how to point the antenna in the correct direction, how much power to use, and how to send data. For this purpose, there are CubeSats with intelligent systems or adaptive programs that can adjust the way they communicate based on context or the conditions.

In most of the missions, straight communication with Earth can be impossible with the constraints of CubeSat in terms of power and antenna size. Alternatively, relay-based designs have been implemented, where CubeSats will forward data to a proximal orbiter or mothercraft that has a larger communication system. This design was shown to work by NASA's MarCO CubeSats, which acted as real-time relays for the InSight Mars lander. Future interplanetary missions can capitalize on CubeSat swarms with Inter-Satellite Links (ISLs) to collaboratively forward data to relay nodes, thus expanding communication range and robustness. Collectively, these design techniques are the foundation of interplanetary CubeSat communications that allow such small spacecraft to conduct sophisticated science and exploration tasks away from Earth in spite of their built-in size and power constraints.

4. Technologies Enabling Deep Space Communication

Deep space CubeSat missions need strong, efficient, and compact communications technologies with the ability to communicate over long interplanetary distances. The radio systems applied in Low Earth Orbit (LEO) are not adequate for deep space because of greater path losses, increased delays, and constrained power budgets. There have been recent developments in space communications technologies that allows the CubeSats to overcome most of these limitations, making telemetry, data transfer, and command operations reliable. This part looks at the major enabling technologies: deployable and high-gain antennas, optical communications systems, Software-Defined Radios, and solutions based on machine learning.

4.1. High-Gain, Deployable, and Phased Array Antennas

High-gain antennas are needed for far-field communication, since they focus energy in a single direction to generate increased signal-to-noise ratios. Due to volume constraints, CubeSats tend to have deployable antennas that unfurl upon deployment, providing an increased effective aperture.

The antennas tend to be lightweight, made of flexible materials such as mesh reflectors or thin-film materials, and compact stowage configured. Phased array antennas provide beam-steering without the necessity for mechanical motion, with better pointing even when the orientation of the CubeSat is changing. Although power and complexity constraints, limit wide use, research is underway into low-power and miniaturized phased arrays for small satellites.

4.2. Optical (Laser) Communication Systems

Laser or optical communication systems provide an attractive alternative to Radio Frequency (RF) systems, because they have greater data rates, narrower beam divergence, and immunity to RF interference. Optical systems can have data rates several orders of magnitude greater than RF, which is critical for transmitting scientific data across interplanetary distances. But optical communication requires accurate pointing and tracking mechanisms, since slight misalignments can result in signal loss. In addition, atmospheric interference (for ground-to-air or ground-based optical links), onboard stabilization, and size issues are still significant concerns for CubeSat-based laser communication systems. Successful demonstrations like NASA's Optical Communications and Sensor Demonstration (OCSD) shows increasing viability of optical systems for deep space CubeSat missions.

4.3. Software-Defined Radios (SDRs)

SDRs are also reconfigurable and flexible with reconfigurability accomplished at the communication protocols in software rather than hardware. CubeSats can dynamically change modulation schemes, frequency, and coding strategies compared to changing mission requirements or unforeseen channel behavior. SDRs also allow for post-launch updates at ease, enabling interoperability and multi-mission capability. JPL's Iris SDR in the MarCO mission is a demonstration to transmit information from Earth for the InSight Mars landing. SDRs are also becoming popular because of their adaptability in deep space missions, although they need more power and computation than fixed-function radios.

4.4. Machine Learning for Link Prediction and Autonomous Recovery

Machine learning (ML) methods are being employed more and more to improve communication reliability and autonomy in deep space networks. ML can be applied in link prediction by examining orbital behavior, ambient conditions, and signal history, to predict link availability and schedule optimization. Moreover, fault detection and recovery systems based on ML enable CubeSats to automatically detect and recover from faults, for instance, loss of communication or hardware deterioration. The methods minimize ground control dependency, which is essential due to the high-latency and short contact duration nature of the deep space environment.

4.5. Power-Efficient and Radiation-Hardened Components

Power-efficient and radiation-resilient technologies are crucial for maintaining uninterrupted communication in hostile space environments. Radiation-hardened power amplifiers, low-noise receivers, and radiation-hard components are being pursued aggressively to lengthen mission times and provide steady link performance when exposed to cosmic radiation.

The development of communication technologies plays a key role in facilitating the reliable and effective deep space mission with CubeSats. Optical communication systems, high-gain and deployable antennas, machine learning algorithms, and Software-Defined Radios together compensate for the complications of long-haul data communications, autonomy, and adaptability. As those technologies further improve and become lighter and more energy-efficient, interplanetary networks of CubeSats will largely be empowered to perform in new ways.

5. CubeSat Network Architectures and Topologies

With advancing interplanetary missions that include constellations of small satellites, CubeSat network architecture and topology have become a critical component for facilitating scalable and reliable communication systems. As opposed to traditional monolithic spacecraft employing single, centralized communications systems, CubeSat networks are designed to be functional in distributed operating modes that afford greater fault tolerance, coverage, and data relay capabilities. The three major topologies adopted in deep space CubeSat missions are constellations, swarms, and cooperative relay-based networks.

Constellations involve the deployment of multiple CubeSats on synchronized orbits or trajectories to provide persistent or extended communication capability. The networks are typically designed such that at any given time, at least one CubeSat would remain in line-of-sight of Earth or a relay to provide a quasi-continuous link. Whereas, this model is satisfactory for missions on Earth, adapting it to interplanetary space requires more sophisticated mission planning and autonomous satellite-to-satellite coordination due to greater distances and limited ground visibility.

Swarm architecture enable a group of CubeSats to present themselves as an ensemble, typically applying distributed control and adaptive action. Swarms are especially best for scientific missions involving spatially distributed measurements, that is, mapping a magnetic field or following an asteroid. Members of the swarm may also share information with their neighbors through Inter-Satellite Links (ISLs) to facilitate local data collection and backhaul to the earth. This structure lessens reliance on a single node and contains redundancy.

Relay distributed systems in collaboration are a hybrid system where CubeSats work together with the nodal satellite to relay information across long interplanetary distances. The nodes in this setup are employed as relays for communication and acquiring data. This setup was successfully employed as an in-real-time relay for communication of NASA's InSight lander during the Mars Cube One (MarCO) mission. Although MarCO itself brought no science data, it supplied an extremely beneficial service of communication that proved a viable method to reach beyond classic relay spacecraft, employing CubeSats.

This achievement is contingent on trusted inter-satellite communication protocols and dynamic network management schemes. Delay/Disruption Tolerant Networking (DTN) and Software-Defined Radios (SDRs) enable the dynamic regulation of data routing and dynamic adjustments in communication parameters with respect to changes in the environment or failure at nodes. Cooperative routing algorithms and mesh networking protocols are also under investigation for maintaining the integrity of CubeSat constellations in space. Rather than relying on a small number of larger spacecrafts, a distributed architecture, built out of numerous cooperating CubeSats offers scalability, fault tolerance, and adaptability. As these architectures develop further, they are likely to form the foundation of interplanetary communication infrastructure of the future, particularly for missions that involve simultaneous exploration of multiple bodies or areas.

6. Challenges in Deep Space Communication and its Solutions

Communicating across interplanetary distances hosts demanding challenges, especially for resource-constrained platforms like CubeSats. Unlike large spacecraft with robust communication subsystems, CubeSats must operate within stringent limitations in power, size, and mass, making deep space communication particularly complex. Some of the major challenges that are faced by the CubeSats during the interplanetary travel is as follows:

6.1.High Latency and Long Signal Delays

One of the most basic interplanetary communication challenges is the tremendous latency caused by the huge distances between planets. For instance, the duration it takes for a signal to propagate from Earth to Mars can vary from 5 to 20 minutes, depending on their positions relative to each other. Such a delay makes real-time communication unfeasible and necessitates spacecraft, including CubeSats, to run autonomously for long periods of time. Such a delay is further magnified for missions to the outer planets or deep space, where round-trip communication may take hours or more. Such high delay causes breakdowns in command-and-control operations and requires onboard smartness and fail-safe mechanisms to provide mission continuity independent of continuous Earth-based control.

To combat the impact of high interplanetary latency, Delay/Disruption Tolerant Networking (DTN) deployment has come as a strong solution. DTN protocols provide onboard data storage in CubeSats and forwarding upon connective link availability, thereby enabling effective delay and disruption handling. The store-and-forward protocol precludes excessive reliance on uninterrupted connectivity and facilitates data delivery over distances. In addition, autonomous operation - where CubeSats operate in real-time based on onboard AI - is increasingly necessary to accomplish mission-critical tasks when ground control feedback in real-time is not possible.

6.2. Low Transmission Power

CubeSats, as small and limited resource platforms by nature, greatly limit their capability for generating and directing power to use in communication systems. In contrast to big spacecraft with strong transmitters and giant solar panels, CubeSats usually use low-capacity batteries and small solar panels. That means lower capability for signal transmission strength, meaning that it is hard for the signals to be received across interplanetary ranges. Consequently, communication from Earth frequently involves the use of highly sensitive ground receivers or the aid of giant relay systems, which is not always practicable. The power limitation also restricts the use of higher-bandwidth communications technologies that require greater energy, for example, high radio frequency or laser systems.

As power generation and storage are limited in CubeSats, using low-power communications methods and power-conserving hardware must be done. Deployable high-gain antennas do not significantly affect signal improvement without necessitating excessive power requirements. Additionally, optical communication units such as laser-based links have higher data rates for lower power than their conventional RF counterparts. Though requiring high accuracy pointing and misalignment sensitivity, they have significant potential for deep space communications with them. Some of the trends that are emerging with miniaturized laser terminals and power-efficient transceivers are making these solutions acceptable for CubeSat-scale missions.

6.3. Bandwidth and Data Rate Constraints

Bandwidth is a precious commodity in space communications, and the CubeSat mission is particularly disadvantaged by virtue of its reliance on limited frequency allocations and low-gain antennae. At limited transmission rates, CubeSats struggle to transmit large volumes of data back to Earth, especially if the mission calls for high-resolution imaging, spectroscopy, or complex scientific experiments. The data transmission rate typically causes a compromise in data quality, update rate, or onboard compression. Additionally, most CubeSats operate on common frequency bands shared by other space- or ground-based systems, and bandwidth competition and interference further degrade communication effectiveness.

To reduce bandwidth limitations, onboard data compression schemes and data transmission on a need-to-know basis can be provided in CubeSats. Artificial intelligence-based onboard processing can filter real-time sensor data, remove redundant or irrelevant data, and send critical information. Besides, sophisticated modulation techniques and coding schemes for channel, techniques like Low-Density Parity-Check (LDPC) and Turbo codes can be used to achieve the highest data rates within the narrow frequency band limit. As communication systems become adaptive, dynamic bandwidth allocation would make it possible for CubeSats to share the spectrum more efficiently, especially when operating in constellations.

6.4. Signal Disruption and Package Loss

The harsh space environment presents several factors that can disrupt CubeSat communication. Space weather events, such as solar flares, can generate electromagnetic interference that impacts signal clarity and integrity. In addition, signal obstruction can occur due to planetary alignment, for example, solar conjunctions where the Sun eclipses in the direct line-of-sight communication between Earth and the spacecraft. These events can lead to substantial packet loss or complete communication blackouts. Without strong error correction mechanisms and buffering strategies, these interruptions cause critical mission information to be lost, particularly when extended relays of data are encountered.

To improve resilience to signal loss and packet loss, Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) protocols can be employed by CubeSats for preserving data integrity. In addition, development of redundant communication pathways through constellations or relay, CubeSats can provide backup for transmitting data when primary links fail. Deployment of a mesh network of cooperative CubeSats can allow distributed routing to improve fault tolerance. Further shielding from signal degradation can be obtained from radiation-hardened electronics as well as adaptive transmission protocols that adaptively alter parameters in line with surroundings.

6.5. Doppler Shift and Frequency Instability

Interplanetary CubeSats operate at high relative speeds, resulting in detectable Doppler frequency shifts between transmitted and received signals. The Doppler shifts can make communications in systems drift out of their allocated frequency bands, becoming less intelligible or losing altogether. Furthermore, because there are limited onboard processing resources and simple radio systems on the CubeSats, real-time compensation for Doppler effects is computationally intensive. Precision tracking, frequency prediction algorithms, and adaptive receivers are necessary, but usually missing on resource-limited platforms, creating a serious problem for achieving stable and clean communication links.

To handle frequency changes caused by high relative speeds, CubeSats may be fitted with Software-Defined Radios (SDRs) that provide real-time frequency agility and dynamic reconfiguration of communication protocols. Such SDRs can automatically implement Doppler correction algorithms to ensure signal lock during communication. In addition, predictive modelling of orbital dynamics allows precise estimation of Doppler effects, which can be pre-compensated. The integration of adaptive frequency tracking and phase-locked loops in the design of CubeSat communication system, greatly improves its stability and performance in long-distance, high-speed communication.

6.6. Absence of Infrastructure

In contrast to Earth-orbiting satellites, which enjoy global ground station and relay satellite networks, interplanetary CubeSats tend to fly alone or rely on massive mission-specific spacecraft to relay their signals. The absence of an exclusive interplanetary communication infrastructure severely limits the capacity of CubeSats to stay in touch with mission control continuously. The restricted line of sight, alignment constraints, and access to Earth-based Deep Space Networks (such as NASA's DSN), adds complexity to mission planning. Constructing and launching a scalable, autonomous network of CubeSats that can serve as a deep space relay mesh remains an active research and development topic.

To counter the lack of an interplanetary communications infrastructure, scientists are working on ideas for autonomous CubeSat relay networks that could function like space-based mobile routers. These encompass Inter-Satellite Communication (ISC) based on RF or optical links to allow CubeSats to relay data between each other until reaching a relay node that can forward to Earth. In addition, missions are being designed with dedicated communication nodes - larger spacecraft or orbiting satellites that offer persistent communication services to proximate CubeSats. Establishing a solar system-wide relay architecture, like Earth's Internet, could revolutionize deep space communication, particularly for small spacecrafts.

6.7. Regulatory Spectrum and Allocation Issues

With an increasing number of CubeSat missions being proposed and launched, management of the spectrum is a growing concern. Spectrum management is coordinated by the International Telecommunication Union (ITU), and it is often a protracted and competitive process to have deep space utilization approved. With the majority of CubeSats operating on amateur or public frequency bands, it is susceptible to interference from satellites or terrestrial-based systems. Additionally, frequency planning for long-duration missions will have to provide for future spectrum congestion and the potential for dynamic frequency reassignment – these capabilities are not yet incorporated into most CubeSat platforms.

Regulatory challenges must be addressed by proactive engagement with the International Telecommunication Union (ITU) and other regulation bodies to obtain allocated frequency allocations for deep space use. Future CubeSat missions would be made even more easier by incorporating frequency agility through implementing SDRs with the ability to switch between bands to avoid interference. Emerging technologies such as cognitive radio systems, permit satellites to sense and utilize available spectrum dynamically based on surroundings, introducing more operational agility. Global coordination among space agencies and commercial companies will also become crucial in crafting an international spectrum-sharing standard for the burgeoning numbers of interplanetary CubeSats.

Though promising, interplanetary CubeSats are faced with a range of communication challenges such as high latency, power limitations, bandwidth restrictions, signal interference, and regulatory hurdles. These challenges constrain real-time control, throughput, and mission reliability. These challenges notwithstanding, advances such as Delay/Disruption Tolerant Networking, autonomous scheduling, Forward Error Correction protocols, and miniaturized high-gain antennas are enabling CubeSats to deal with the demands of deep space communications. Conquering these challenges is essential to achieving the complete scientific and exploratory potential of CubeSat missions beyond Earth orbit.

7. Prospects

As CubeSats mature, their application to interplanetary missions is likely to grow much larger. Perhaps the most promising development is the achievement of a Solar System-scale interplanetary internet, in which CubeSats are used as independent nodes in a Delay/Disruption Tolerant, self-healing Network. This would allow for more robust and scalable data transfer between planetary systems and Earth, enabling a broad range of scientific and exploratory missions. Standardization of protocols and interfaces will also pick up speed, allowing for improved interoperability across spacecraft from various agencies and their commercial partners. With deep space missions making wider use of open architecture and plug-and-play elements, this will bring about quicker deployment cycles and lower costs. Furthermore, artificial intelligence to manage the network, detect faults, and make autonomous decisions will need to be incorporated. CubeSats need to work autonomously, if not remotely, with little or no human input, and will need to adjust its communication plans dynamically as a function of shifting mission conditions. On the hardware front, continued miniaturization of transmitters with high power, optical communication networks, and deployable antennas will continue to enhance the competence of CubeSats to operate effectively in deep space. Technologies like phased arrays, laser communication terminals, and Software-Defined Radios will be used more extensively, even under the constraints of a 3U or 6U CubeSat size.

In summary, the future of interplanetary CubeSat communications is to build smart, expandable, and autonomous networks that will push the boundaries of space exploration without affecting cost-effectiveness and reliability. These technologies will not only support CubeSat missions but also form part of larger revolution in the way humankind faces and explores the universe.

8. Conclusion

CubeSats are changing the way by which the space is explored with the offering of low-cost miniaturized space vehicles that have the capability of conducting meaningful missions beyond Earth. With all that, however, comes many difficulties in transmitting and receiving data through these small space satellites in deep space. Such are the prolonged communication delays, weak signals with minimal power, low data rate, signal degradation due to space weather, and no communication infrastructure in deep space. To counter these problems, new technology and methods are being developed. For example, Delay/Disruption Tolerant Networking (DTN) helps in managing long delays, while optical (laser) communication and smart antennas improve data transfer. AI and Software-Defined Radios (SDRs) are also making CubeSats smarter and more interactive during missions. Flying in swarms or constellations of CubeSats that work together can help to make more effective and durable communication networks in space. As technologies advance, CubeSats will be able to conduct increasingly advanced missions on their own. CubeSats will have an even bigger part to play in the exploration of the solar system in future years. Research and collaboration between scientists and space agencies will be crucial to making deeper space CubeSat missions more successful and reliable.

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