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Energy Efficient Designs and Technology of Satellites.

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Abstract
Due to the rapidly growing demand for high-performance communication services, ever-changing constellations and technology, energy efficiency is being taken under major consideration and necessity in the designing of a satellite and its systems. The energy consumption of a satellite bestows great challenges in its sustainability and operational costs. This review will examine the role of energy and its consumption in various subsystems of a satellite like communication links, on-board payloads, framework of satellites, etc. , and analyse the strategies like power control, use of renewable energy for designing energy-efficient systems of satellites, keeping in mind the advancements in technology and software, with case studies that show successful implementation of such strategies. Environmental factors have also been taken into consideration, highlighting the importance of aligning energy-efficient systems in such a way that they do have a significant impact on the environment.

Keywords: Energy Efficiency, Sustainability, Operational Costs, Power Control, Renewable Energy, Satellite Framework, Environmental Factors.

1. Introduction

As modernisation is increasing rapidly, the need for satellites is increasing. It helps revolutionise global connectivity by enabling real-time communications across vast areas, provides services such as navigation, broadcasting, surface monitoring, propulsion, thermal control systems, and for weather conditions. Countries use satellite communications for national security and private military communications. As the number of satellites increases, the energy consumption increases. There are multiple challenges faced during satellite communication such as interference, signal disruption, propagation delays that motivate many to research and write about it.

The working of satellites, ground stations, and correlated systems consumes a large amount of energy and power sources for proper functioning, which can lead to environmental degradation, carbon emissions, an increase in operational costs, and the overall budget required. So the main question comes—how can satellite systems be designed to reduce energy consumption while maintaining operational efficiency? Satellites should be designed in such a way that they not only reduce operational costs but also extend the life of a satellite, reduce carbon emissions, enhance communications, and reduce the risks of power failure.

Now, as the world becomes more interconnected, the demand for satellites is growing exponentially, and so the number of satellites is stationed in orbit. Many countries and private companies invest heavily in these satellites, aiming to provide connectivity across rural and urban areas. Satellite functioning now calls for **energy optimisation**, which would give maximum performance without compromising the services it will provide along with minimum waste. To minimise energy consumption, error correction codes, power control techniques, and advanced modulation schemes are used. The conventional way to optimise energy is the use of solar panels for energy generation, but it comes with its cons. Satellites can face setbacks during eclipses when they pass behind the Earth, which leads to the consumption of stored energy, leading to a reduction in the life span of the satellite.

Achieving energy efficiency often compromises other functions and operations like data rate and reliability; therefore, it is important to manage and balance out these trade-offs to meet the desirable outcome with minimum energy consumption. This paper will explore the key aspects of energy-efficient designs of systems of a satellite and how they can be integrated into payloads of a satellite, communications, onboard systems, etc. This paper will also highlight the rapidly evolving **Low Earth Orbit constellations** and their impact on energy consumption.

Therefore, we should look forward to designing, building, and providing high-efficient and quick communication links by making sure that the satellites are **sustainable, cost-effective, have advanced technology, and are environmentally friendly.**

2. Methodology

The primary methodology of gathering data and information was through a structured and planned approach called systematic literature review, which involves analysing pre-reviewed research papers, technical reports, and articles. The purpose was to provide a detailed analysis of energy-efficient satellite designs, technologies, and strategies and how they can and are incorporated into a satellite contributing to sustainable satellite operations.

The information was extracted from well-known and established platforms and sources such as:

- **IEEE Xplore**
- **Google Scholar**
- **Science Direct**
- **Orion Scholar Journals**
- **Research Gate**

Proper research and articles were taken into consideration to ensure that the works were not outdated and obsolete but reflected more recent advancements and technologies in satellite communications technology.

3. Results

Now, as we know, there are several components of satellites that require energy for their working, such as communication transponders, antennas, batteries, solar panels, transmission equipment, etc. Each subsystem of a satellite requires and consumes energy according to functionality and mission

requirements. They should be designed in such a way that they are able to access their power requirements to identify patterns and opportunities to optimise energy.

The systems consume energy for solar energy generation, charging of the batteries, power conversion, its transmission, data and information transfer, temperature regulation, stabilisation, altitude determination. It is also used by thrusters, gyroscopes, reaction wheels, and algorithms based on orbital dynamics and altitude.

Techniques such as **Low Density Parity Check (LDPC) codes** and **Adaptive Modulation** allow satellites to transmit more data with less power. Usage of **high-efficiency photovoltaic cells** and **solar arrays** reduces dependency on conventional power sources, resulting in an increase in the operational lifespan of the satellite.

Energy-efficient satellites help in reducing overall carbon or greenhouse gas emissions associated with their operations, optimise operational costs, and support broader sustainability goals including long-term viability and resource management.

Some common approaches to attain such a satellite will be to use **efficient modulation schemes, error correction coding, and power control techniques.** Maximising solar power generation by optimising and configuring solar panels with respect to the Sun and using advanced battery technologies and energy storage systems to increase energy lifespan and reliability, and implementation of **passive and active thermal control measures** to minimise temperature fluctuations and reduce the consumption of energy that is required for cooling and heating. Optimising attitude determination and control algorithms to minimise the energy required for spacecraft stabilisation and manoeuvring. By implementing these few strategies, we can optimise as well as monitor energy consumption across all subsystems of a satellite so that we can achieve energy efficiency, reliability, and sustainability by cutting down the overall budget required.

4. Energy Efficient Techniques, Designs, and Power Control

Leo and Geo Satellites:
Now, several energy-efficient techniques have been used and employed to optimise data transfer while simultaneously saving energy too.

Low Earth Orbit (LEO) satellites offer reduced signal latency, improved coverage, and enhanced capacity. They are being more preferred since they help in establishing **mega-constellations** for **greater internet connectivity** and **global reliable coverage** directly from space.

GEO, Geostationary Earth Orbit satellites, operate at approximately 35,700 km above the equator, matching Earth's 24-hour rotation to stay fixed over one point. They provide constant, **massive coverage** for television broadcasting, weather monitoring, face minimal interference, and telecommunications, enabling ground antennas to remain stationary, though they suffer from high latency (~240-280 m/s). They use **High-Throughput Satellite (HTS) technology**, offering more capacity through spot beam technology.

LEO is generally the preferred choice for high-speed internet and real-time data as they are closer to Earth. They can handle video calls, online gaming, and high-frequency trading that GEO simply cannot support due to lag. They are generally preferred for constant television broadcasting and weather monitoring, meteorological studies, because they do not suffer from "handovers", i.e the momentary break when switching between moving satellites.
However, LEO satellites have a few disadvantages too. They have a tough balancing i.e they need to stay small to keep launch costs down, which means using tiny batteries and relying on solar power. They spend a lot of time in the Earth's shadow, therefore, their power is tight. This makes it a major challenge to keep the satellite running efficiently without sacrificing service quality.

Starlink, handled by SpaceX, is the world's largest satellite constellation, with over 6,750 LEO satellites in orbit. It uses highly efficient, sustainable power systems, specialised propulsion for orbital maintenance, and smart, low-power operational design. It uses a single **highly efficient solar array** to generate electricity, and is the first spacecraft to use **Argon propellant,** which is **cost-efficient and easier to source than Xenon thrusters.** It is designed in such a way that it minimises atmospheric drag at low altitudes, which reduces the need for frequent, energy-consuming manoeuvres. While space is a vacuum, the satellites utilise passive radiative cooling to manage high-temperature loads from internal electronics, minimising the need for active cooling systems that would consume power.

5. Protocols and Techniques:

OFDM, that is Orthogonal Frequency Division Multiplexing, improves energy efficiency and capacity by splitting bandwidth into multiple subcarriers to transmit data simultaneously. However, external interference from satellites or weather can still degrade performance and drive up power use. Power control and adaptive modulation optimise satellite energy efficiency by dynamically adjusting to channel conditions and traffic. These techniques **maximise spectral efficiency** while **minimising power consumption** and interference. Algorithms regulate transponder power to maintain signal quality while saving energy. **Energy-efficient FEC codes, such as Low-Density Parity-Check (LDPC) codes and Turbo codes,** offer high coding gain and low decoding complexity, making them suitable for satellite communication systems.

Most satellites use **solar panels** as their source of energy, which are mounted on the exterior of a satellite to generate electricity. They are a r**enewable source of energy,** making the spacecraft less dependent on conventional sources. The panels are accompanied by **batteries** which store **excess energy** generated by the solar panels, which help generate power during eclipses or when the panels are not generating a sufficient amount of power. Now, different types of batteries are used, such as nickel-cadmium (NiCd), nickel-hydrogen (NiH2), and lithium-ion (Li-ion) batteries. Energy storage solutions must be carefully designed to optimise energy density, lifespan, and reliability while meeting the power requirements of the satellite mission.

High Efficiency Power Amplifiers (HEPAs) are used in satellites, which improve the **efficiency of signal amplification** and ensure that less energy is consumed and wasted in the process, making the system more energy efficient.

Thermal insulation and heat pipes regulate the temperature of the onboard components by releasing heat into space. They rely on natural thermal gradients and physical properties to prevent overheating and thermal equilibrium. Active thermal control systems use heaters, coolers, and thermal switches to actively regulate the temperature of critical subsystems and components.

Adopting energy-efficient models, designs, and techniques in satellite communication systems offers great multiple impacts in different aspects. Integration of solar panels in satellites reduces the dependency on fossil fuels, thereby reducing carbon emissions associated with its operations and mitigating fuel costs. This also helps in reducing the overall operational costs required for a satellite mission and increasing its lifespan by minimising the wear on batteries and power systems.

6. Case Studies:

Iridium NEXT satellite constellation is a $3 billion second-generation network of 66 LEO operational satellites at approximately 627-720 kms. It provides 100% full global coverage, including the Earth poles, with improved data efficiency and throughput. Attitude determination is handled by Multi-**Head Star Trackers (MHSTR),** which minimises energy consumption as compared to traditional systems. The system is highly optimised for Internet of Things (IoT) devices, with modems that stay in "sleep mode" by default and only turn on for milliseconds during transmissions. The satellites utilise sophisticated thermal modelling to handle heat efficiently, contributing to longer operational life and lower power penalties.

Globalstar Second-Generation Satellite Constellation includes energy-efficient transmission protocols and error correction coding techniques and **bent-pipe technology** to enhance spectral efficiency and reduce power consumption. They provide high-quality mobile satellite services (MSS). T**he 16 transponders from C to S band** are optimised for efficient signal transmission, focusing power on the necessary transmission bands to minimise waste. T**he system uses a patented "gateway diversity" technique that allows for efficient satellite handovers.** This reduces the time a satellite needs to waste power transmitting, as it can pass the signal to the next available satellite or ground gateway seamlessly.

ISRO's SPADEX, successfully launched at the end of 2024, demonstrates in-orbit power transfer from one unit to another. This eliminates the need for every satellite component to carry massive, redundant battery backups or bulky solar panels. Instead, specialised "power-hub" modules can recharge companion satellites dynamically, paving the way for multi-satellite space stations and low-energy servicing fleets.

JAXA's SLITS/ VLEO satellites optimise energy by heavily **relying on a mix of hyper-streamlined aerodynamic shapes and ultra-efficient ion engines** that continuously counter drag using only minimal electric energy harvested from solar panels rather than draining vast chemical fuel reserves to prevent orbital decay. By replacing heavy and short-lived chemical propellants with **highly efficient solar-powered ion engines,** the satellite optimises its overall launch energy, extending operational life at low altitudes from weeks to several years.

SpaceX's Starlink satellite constellation implements innovative power management and thermal control solutions to optimise energy efficiency and operational reliability. These satellites feature solar panels with high efficiency and advanced power regulation circuits to maximise solar power generation. Starlink also utilises dynamic power management techniques and thermal modelling tools to ensure optimal performance under varying environmental conditions.

What Did We Learn and Future Recommendations:

Future satellite systems must adopt integrated, energy-efficient designs from the start. This proactive approach minimises power consumption and optimises performance over the entire development cycle. Doing so ensures the sustainability and cost-effectiveness of space operations. Integrating energy-efficient components, subsystems, and protocols into the overall architecture maximises savings and performance. Implementing ongoing monitoring and, as suggested in, analysing operational data helps to identify energy-saving opportunities. By embedding energy-aware designs such as hardware and protocols, from the start, satellites consume less power. Following this up with constant monitoring allows operators to fix inefficiencies over time, maximising the overall utility and lifespan of satellite assets.

Operators should **secure energy efficiency certification** from regulators to prove compliance with power, spectrum, and environmental standards. **Energy efficiency certification programmes** verify that satellite systems meet predefined sustainability criteria, ensuring reduced power consumption and environmental impacts. Integrating renewable energy sources like solar and wind into operations allows operators to directly lower carbon emissions.

7. Conclusion

This study explores energy efficiency in satellite design, focusing on subsystems like communication links, payloads, and the satellite framework. It examines strategies such as power control, renewable energy utilisation, and advanced technologies to optimise energy consumption while maintaining operational efficiency. The study also considers environmental factors and the impact of Low Earth Orbit constellations on energy usage.

LEO satellites are preferred for high-speed internet and real-time data due to their proximity to Earth, supporting applications like video calls and online gaming. Energy efficiency is crucial in satellite communication, achieved through techniques like OFDM, power control, and adaptive modulation. Integrating energy-efficient designs and components, along with ongoing monitoring, can optimise performance and extend the lifespan of satellite assets.

To meet the soaring global demand for connectivity without harming the environment, satellite operators and manufacturers are developing highly energy-efficient technologies. This sustainability drive relies heavily on integrating renewable energy sources, particularly solar power, to run onboard systems cleanly. Additionally, the industry is adopting **green propulsion systems to replace traditional, toxic fuels.** Together, these advancements ensure that modern satellite operations can expand global network coverage while drastically minimising energy consumption and carbon footprints.

Ultimately, building a greener satellite industry depends on our shared commitment to look beyond traditional boundaries. By i**nvesting in smart energy research, establishing clear official standards, and empowering our teams** to lead the way, the satellite communication industry can achieve higher levels of energy efficiency while running better, more efficient networks for a truly sustainable future.

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