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Analysis of the Impacts of Space Environment on the Communication Subsystem of A Satellite

Aminu Musa Chindo[1], Ayegba Abdullahi[2], Jude A. Adeleke[3], Akulaga Terfa[4]

[1,2]Engineering and Space Systems Department, National Space Research and Development Agency, Abuja, Nigeria
[3]Information Communication Technology Department,
National Space Research and Development Agency, Abuja, Nigeria
[4]Geosmart Digital Solution Department, National Centre for Remote Sensing, Jos, Nigeria
[1,3]School of Computing and Information Technology, African University of Science and Technology, Abuja, Nigeria

ABSTRACT

This research work was aimed at investigating the impacts of the space environment on the communication subsystem of a satellite. The research employed the explanatory and review research methods to discuss what a communication subsystem of a satellite is and its functions, as well as the components making up the subsystem. The study also looked at some ways the space environment can impact negatively the communication subsystem of a satellite. From the analysis, it was revealed that some components of the communication subsystem of a satellite are antennas, transponders, modulators, demodulators, power amplifiers, receivers, and transmitters. It was also observed from the analysis that some impacts of the space environment on the communication subsystem of any satellite, irrespective of the type, are radiation effects, extreme temperature variations, vacuum conditions, space weather, atomic oxygen, charging, and electrostatic discharge. It was concluded from the results that the space environment has a serious impact on the communication subsystem of a satellite. These findings are relevant for satellite engineers, space sector scientists, GSM service providers, academics, and communication links designers.

KEYWORDS: *Atomic oxygen, Communication subsystem, Power amplifier, Space weather, Satellite, Vacuum condition.*

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1. INTRODUCTION

Space is a region beyond the Earth's atmosphere. The space environment is the conditions in space, such as space weather, radiation, temperatures, gravity, geomagnetic fields, plasmas, space junk, stars, planets, moons, meteoroids, comets, and the upper atmosphere of the Earth. It is a region characterized by various phenomena such as extreme thermal gradients from direct solar exposure to deep-space cold; intense ionizing radiation from solar particle events, galactic cosmic rays, and trapped particles in the Van Allen belts; and variable solar and geomagnetic activity that induces drag and electromagnetic disturbances. These conditions collectively impose mechanical, thermal, electrical, and material-degradation stresses on satellites or spacecraft. When a wireless communication system is applied to a satellite component as a small communication module, the radiation tolerances of the control IC and wireless module are important. Even if the radiation tolerance of the latter is high, its overall reliability will decrease if the radiation tolerance of the former is extremely low (Toshihiro et al., 2022). Space radiation presents a significant challenge to the reliability and performance of optoelectronic devices used in satellite applications. The primary sources of space radiation include solar radiation, cosmic rays, the Van Allen radiation belts, solar flares, geomagnetic storms, micrometeoroids, and space debris, as referred to in Fig. 1. Each of these sources contributes to the degradation of semiconductor materials through mechanisms such as ionization, defect formation, annealing, and other effects on materials and devices in spacecraft. The specific sources of radiation that affect a particular spacecraft will depend on its orbit and the time of year (Sulaiman et al., 2025).

The effects of radiation on semiconductor devices can be roughly classified into total ionizing dosage effects and single-event effects (SEEs). In the former, the effects of charged particles accumulate in the semiconductor and change its characteristics over time; in the latter, the charged particle effects temporarily cause a single-event upset (SEU) in the memory or a single-event latch-up (SEL) in the switching device (Ikeda et al., 2005).

High-energy trapped electrons in the Van Allen belts pose a threat to the survivability of orbiting spacecraft. Two key radiation effects are total ionizing dose and displacement damage dose in components and materials, both of which cause cumulative and largely irreversible damage. During an extreme space weather event, trapped electron fluxes in the Van Allen belts can increase by several orders of magnitude in intensity, leading to an enhanced risk of satellite failure (Hands et al., 2018). The sources of radiation in the space environment present significant challenges to the reliable operation of optical satellite communication systems (Yaacob et al., 2017, and Liu et al., 2020). This work takes a critical look at how the performance of the communication subsystem of a satellite is being affected by the space environment, a work that is not given adequate attention it deserves as observed in the works reviewed so far.

Fig 1: Space environment. (Source: aerosociety)

2. Materials and method

The materials used for this work are secondary materials consisting of library books, journals, and online works published in recent years. The work made use of the review and explanatory research methods. The explanatory research method was used to analyse or discuss the various components of the satellite communication subsystem, while the various impacts of the space environment on the communication subsystem of a satellite were treated using both the review and explanatory research methods. The use of the explanatory research method was to allow more discussion of the topic, while the review method was to allow the discussion of the findings of some researchers in the related works recently carried out.

3. Communications Subsystem of a Satellite

3.1. Communications Subsystem

The communications subsystem of a satellite is the subsystem or part of the satellite that is responsible for the transmission and reception of information or data between the satellite and the ground station, satellite signal-enabled devices on the earth, or another satellite. The communication subsystem of a satellite is the part responsible for sending information from space to Earth and receiving commands from ground stations. Apart from communication satellites, all other types of satellites, such as earth observation satellites, navigation satellites, weather satellites, security satellites, etc., have their communication subsystems. The communication subsystem provides the interface between the satellites and ground systems. The communication subsystem itself consists of antennas, a transmitter, a receiver, a transponder, an oscillator, a high-power amplifier, a modem, waveguides, a switch, etc., and transceivers to be able to communicate with the monitoring stations, sending collected data and receiving instructions from them. These components help the subsystem to send and receive information to and from the earth. The information sent from the earth to the satellite is called the uplink. The information sent from the satellite to the ground is called "downlink," and the information or message sent from one satellite to another satellite is called "crosslink." The communications subsystem receives and demodulates uplink signals and modulates and transmits downlink signals. Also, a satellite can be tracked by measuring the Doppler shift and the direction of arrival of its communication signal or beacon in order to determine its position and velocity. Doppler shift is defined as the change in wavelength or frequency of a wave when the observer and the source are moving relative to each other.

Another importance of the communication subsystem of a satellite is that payload mission data and satellite housekeeping data pass from the spacecraft through this subsystem to operators or ground stations. Also, the commands from the earth station or control center pass to the spacecraft through the communication subsystem to control the spacecraft and to operate the payload. These messages are collectively called TTC (Telemetry, Tracking, and Control). While telemetry (T) deals with the data sent by the satellite from space to the ground station, such as battery voltage, temperature of the components, fuel tank pressure, condition of the transmitter and receiver, etc., tracking deals with the measure/assessment of the satellite's position and velocity from the ground station, and command deals with the sending of instructions to the satellite in space from the ground station. Some of the commands or instructions are firing the thruster for orbital change, switching to a backup component, putting the satellite in safe mode during an eclipse, and turning the direction of the beam of the satellite signal to a given direction.

3.2. Components of the satellite communication subsystem

The following are some components or parts of the communication subsystem of a satellite.

A. Antennas

An antenna is a device used for the transmission and reception of electromagnetic waves. It acts as a bridge between electrical signals and radio waves. When transmitting, it converts electrical energy into electromagnetic waves that travel through space, and when receiving, it captures these waves and converts them back into electrical signals. Antennas are typically made of conductive materials like metal and are designed to operate at specific frequencies. In terms of satellites, antennas are one of the most essential components of the communication subsystem. They enable satellites to send and receive signals over very long distances between space and the ground or earth. Without antennas, communication between satellites and ground stations would not be possible. Common types of antennas used on satellites are dish (parabolic) antennas for focused communication, horn antennas for high-frequency applications, helical antennas for circular polarization, phased array antennas for electronic beam steering, and wire antennas for simpler uses.

B. Transponders

A transponder is an electronic device used to receive, process, and retransmit signals in a communication system. It acts as a link between a signal source and its destination by automatically taking in a signal, modifying it, and then sending it out. In simple terms, it ensures that information can travel over long distances without being lost or distorted. A transponder is a vital part of the communication subsystem of a satellite. When a signal is sent from a ground station or the earth, it reaches the satellite as a weak signal due to the long distance it has traveled from the earth's surface. The transponder receives this signal, amplifies it to restore its strength, and then shifts it to a different frequency to prevent interference. After processing, it retransmits the signal back to Earth. Although there may be many, these processes occur very quickly and continuously, which makes satellites handle large amounts of data in real time.

C. Modulators and Demodulators

A modulator is an electronic device that converts digital or baseband information such as audio, video, or text into a high-frequency signal that is suitable for transmission or sending out. It does this by combining the information signal with a carrier wave, a process known as modulation. This conversion allows the signal to travel efficiently over long distances, especially through space or across communication channels. A demodulator, on the other hand, is a device that performs the reverse function. A demodulator is an electronic device that converts a received high-frequency signal into digital or baseband information such as audio or text. It receives the transmitted high-frequency signal and extracts the original information from it through a process called demodulation. In simple terms, it recovers the data that was embedded in the carrier wave so that it can be understood and used. The modulators and demodulators are essential components of the communication subsystem of a satellite. The modulator prepares the signal for transmission from the ground station or satellite by converting it into a radio frequency form that can travel through space. Once the signal reaches its destination, the demodulator processes it to retrieve the original data. Together, they ensure that information can be transmitted clearly and accurately over long distances. Without modulators and demodulators, reliable communication between satellites and Earth would not be possible, as signals would either fail to travel efficiently or could not be properly interpreted at the receiving end.

D. Power Amplifiers

A power amplifier is an electronic device used to increase the strength or power of a signal so that it can travel long distances without significant signal loss. In communication systems, it ensures that transmitted signals are strong enough to be detected clearly at the receiving end or the horizon. In satellite communication, signals weaken as they travel across the very long distance between Earth and space. If these signals were not strengthened, they would arrive too weak to be detected or useful. Power amplifiers solve this problem by boosting the signal before it is transmitted back to Earth, ensuring clear and reliable communication. There are two common types of power amplifiers used in satellites. Traveling Wave Tube Amplifiers (TWTAs) are highly efficient and are commonly used for high-frequency and high-power applications. Solid-State Power Amplifiers (SSPAs), on the other hand, are smaller and more reliable and are increasingly used in modern satellite systems due to their durability and efficiency.

E. Receivers

A receiver is an electronic device used to detect and capture incoming signals and convert them into a form suitable for processing. It serves as the entry point for signals in a communication system and ensures that transmitted information is picked up at the receiving end. In satellite communication, receivers play a critical role because signals arriving from Earth are usually very weak after traveling long distances through space. The receiver is designed to detect these faint signals, separate them from background noise, and prepare them for further processing by components such as the transponder and demodulator.

F. Transmitter

A transmitter is an electronic device used to generate and send signals from one point to another in a communication system. It converts information into a suitable form, amplifies it, and transmits it through a medium such as space in the form of electromagnetic waves. In satellite communication, the transmitter plays a crucial role in sending signals from the satellite back to Earth or from a ground station to the satellite. It takes processed information such as data, voice, or video and prepares it for transmission by converting it into a radio frequency signal as well as boosting its strength. This ensures that the signal can travel over long distances without losing its quality.

G. Filters

A filter is an electronic device that is used in communication systems to allow desired signals to pass through while blocking unwanted signals and noise. A filter helps to separate useful frequencies from interference, ensuring that only clean and relevant information is processed. In satellite communication, filters are very important because multiple signals often travel close together in space, and without proper filtering, they could overlap or distort each other. In satellite systems, filters remove unwanted noise and interference, ensuring signal quality is being transmitted or received.

H. Multiplexers

A multiplexer is a device that combines multiple signals into a single communication channel so they can be transmitted together. Instead of sending each signal separately, a multiplexer efficiently packages several data streams such as different TV channels, voice calls, or internet data into one signal for transmission. At the receiving end, the signals are separated again for proper use by a device called a demultiplexer. In satellite communication, multiplexers maximize the use of limited bandwidth by allowing multiple signals to share the same transmission path.

4. Effects of the Outer Space Environment on Satellite Communication Subsystems

Unlike ground-based communication systems that function under relatively stable atmospheric conditions, satellites are constantly exposed to extreme physical and electromagnetic forces. These conditions directly affect the components of the communication subsystem such as antennas, receivers, transponders, amplifiers, and others in different ways that can reduce performance or even cause failure. Some of the effects are as follows.

4.1. Radiation Effects

"Radiation effect" means the damage or changes caused when high-energy particles in space (like cosmic rays or solar radiation) hit satellite materials or electronics, sometimes leading to malfunctions or gradual degradation. One of the most significant threats to satellite communication systems is high-energy radiation. This radiation comes mainly from the Sun and from deep space in the form of cosmic rays. When radiation strikes the electronic components of a satellite, it can interfere with their normal operation. Radiation can distort signals, corrupt data, or temporarily shut down parts of the communication system. In more severe cases, prolonged exposure can permanently damage electronic circuits. This is why satellites often use specially designed radiation-hardened components, but even these are not completely immune. According to Sulaiman et al. (2025), ionizing radiation leads to gradual degradation of optoelectronic and RF components, significantly affecting signal integrity and system reliability. The work reported that prolonged exposure reduces the lifespan of communication devices and introduces performance instability in transponders and receivers. Also, Zhu et al. (2026) demonstrate the need for radiation-tolerant RF systems, noting that conventional communication electronics are highly vulnerable to radiation-induced faults such as single-event upsets and cumulative damage. The authors highlight how radiation directly affects signal amplification and modulation processes, which will lead to a weak or unprocessed signal, thus a serious challenge.

4.2. Extreme Temperature Variations

Extreme temperature variations deal with a situation in space in which objects can swing between very hot and extremely cold temperatures as a result of no atmosphere to regulate heat, which can cause materials to expand, contract, and weaken over time. When a satellite is exposed to direct sunlight, its surface temperature can rise to as high as 100°C or above. In the same way, when this same satellite moves into the Earth's shadow, the temperature can drop below -150°C. These dramatic changes occur repeatedly as the satellite orbits the Earth. Such extreme temperature variations have a direct impact on physical components like antennas and amplifiers, as they will cause unusual expansion and contraction repeatedly. This is because materials expand when heated and contract when cooled. Over time, this continuous cycle of expansion and contraction can lead to material fatigue, weakening the structure of components. For antennas, even slight deformation can affect their alignment and signal direction, reducing communication efficiency. In the same way, amplifiers and other electronic devices can also behave differently at extreme temperatures, sometimes becoming less efficient or unstable.

In the work by Kashyzadeh et al. (2025), it was explained that thermal cycling, which is caused by repeated transitions between sunlight and shadow, induces structural fatigue in satellite materials**,** leading to deformation and eventual component failure. This has direct implications for antennas and amplifiers, where precision and stability are essential. In a related study, Arsavarthini et al. (2025) highlight that antenna performance is highly sensitive to environmental conditions, particularly temperature changes, which can alter electromagnetic properties and radiation patterns. This affects communication efficiency and signal directionality.

4.3. Vacuum Conditions

Vacuum conditions deal with the "empty" nature of space, with no air or pressure. On Earth, air plays an important role in cooling electronic devices because the heat generated by components is carried away through convection. In space, however, there is a complete vacuum, meaning there is no air to remove heat. This creates a major challenge for components like power amplifiers and transponders, which generate a significant amount of heat during operation. Without proper thermal management, these components can overheat, leading to permanent damage of the components or their reduced performances. To cope with this, satellites rely on special cooling techniques such as heat sinks and radiators that dissipate heat through radiation rather than convection. As seen in the work by Kameda et al. (2022), which evaluated communication components in low Earth orbit, it was stated that lack of atmospheric cooling significantly affects transceiver performance**,** requiring advanced thermal control systems to prevent overheating. Additionally, Tubbal et al. (2025), in their review of CubeSat communication subsystems, note that power dissipation in vacuum conditions must be carefully managed, as overheating can degrade amplifiers and onboard processing units.

4.4. Space Weather

Space weather deals with the conditions in space, which are driven mainly by the Sun, such as solar flares and geomagnetic storms, which can interfere with satellite operations and communications. The Sun occasionally releases bursts of energy known as solar flares, along with charged particles that travel through space. These events are part of what is called space weather. When such disturbances reach a satellite, they can create strong electromagnetic interference, which disrupts the signals being transmitted and received by antennas, and it can overwhelm receivers and filters designed to process clean signals. In a situation of intense solar activity, communication signals may become noisy, distorted, or completely lost for short periods. In the work by Min et al. (2025), it was shown that solar radiation and charged particles can degrade satellite communication link performance and disrupt satellite network operations, especially in large constellations. In the same way, Tubbal et al. (2025) emphasize that communication subsystems must be designed to withstand electromagnetic interference caused by solar activity, which can affect signal reception and filtering processes.

4.5. Atomic Oxygen

Atomic oxygen is defined as a highly reactive form of oxygen found in low Earth orbit that can slowly erode and damage the surfaces of satellites. In Low Earth Orbit (LEO), satellites encounter a unique environmental factor known as atomic oxygen. Atomic oxygen is extremely corrosive, and when it comes into contact with satellite surfaces, it gradually erodes them. Over time, this erosion can damage exposed components such as antennas and outer protective layers. For communication systems, this means that antenna surfaces may lose their smoothness or structural integrity, reducing their ability to transmit and receive signals or reflect the signal effectively. Kashyzadeh et al. (2025) identify environmental degradation mechanisms, including surface erosion caused by reactive particles like atomic oxygen, which affect external satellite components. Complementing this, Kameda et al. (2022), in their work, reported that long-term exposure of satellite components to the LEO environment, including atomic oxygen, can lead to material deterioration in communication hardware, particularly exposed antenna surfaces.

4.6. Micrometeoroids and Space Debris

Micrometeoroids are tiny particles of rock or metal traveling at very high speeds in space that can strike spacecraft and cause small but potentially serious damage, while man-made objects like broken satellites or fragments from past missions that remain in orbit pose collision risks to active spacecraft. Space is filled with tiny particles known as micrometeoroids, as well as man-made debris from past missions. These objects travel at extremely high speeds, and so, even very small particles can cause serious damage when they collide with a satellite. A direct impact on communication components such as antennas or external hardware can lead to cracks, misalignment, or complete failure. Unlike on Earth, there is no easy way to repair such damage once the satellite is in orbit. That is why Kashyzadeh et al. (2025), in their work, highlight that space debris collisions are a leading cause of structural and functional failures in satellites and that it affects both external and internal systems. Similarly, Min et al. (2025) report that debris environments significantly influence network reliability and node performance in satellite constellations**,** as even minor damage can disrupt communication links.

4.7. Signal Attenuation

Signal attenuation is defined as the weakening of a communication signal as it travels through space or the Earth's atmosphere, which can reduce the quality or strength of transmitted data.

Although satellites operate in space, their signals must pass through the Earth's atmosphere when traveling to and from ground stations. When this signal travels in space either to or from the satellite, it can be affected by environmental conditions such as rain, clouds, and atmospheric gases. This results in signal attenuation, where the signal becomes weaker, or even scattered, where the signal is spread out or redirected. As a result, antennas, receivers, and transponders may receive signals that are weaker or distorted, reducing the quality of communication. This is why you may sometimes experience signal loss during heavy rainfall when using satellite TV or internet services. According to Tubbal et al. (2025), the satellites' communication links are affected by environmental conditions across space and atmospheric boundaries, leading to reduced signal quality and reliability. Furthermore, Min et al. (2025) show that environmental effects influence not just individual links but overall network-level performance, particularly in high-frequency communication systems.

4.8. Charging and Electrostatic Discharge (ESD)

Charging and electrostatic discharge are defined as the sudden release of electrical charge built by the satellite from the surrounding environment. In space, satellites are surrounded by charged particles, especially in regions like the Earth's magnetosphere. Over time, these particles can accumulate on the satellite's surface, creating electrical charge buildup**.** When this charge suddenly releases, it causes electrostatic discharge (ESD), which i**s** a rapid flow of electricity that can damage sensitive electronic components. When this happens, devices such as modulators, receivers, and multiplexers that are vulnerable to such discharge can be affected. Electrostatic discharge is very powerful and dangerous, as it can lead to temporary circuit or device malfunctions, data corruption, or even permanent failure of circuits. In the work by Kameda et al. (2022), it was observed that space environment interactions with electronic components can lead to unexpected behaviour in transceiver circuits**,** partly due to charge accumulation. In addition, Sulaiman et al. (2025) in their research stated that radiation and charged particles contribute to electrical disturbances and degradation in electronic systems, which can trigger failures in sensitive communication components.

5. Conclusion

This research work investigated the impacts of the space environment on the communication subsystem of a satellite. The research, which employed the use of explanatory and review research methods, discusses what a communication subsystem of a satellite is and its functions, as well as the components making up the subsystem. The work also highlighted some of the ways space environments have impacted or can impact negatively the communication subsystem of a satellite. The analysis revealed that some components of the communication subsystem of a satellite are antennas, transponders, modulators, demodulators, power amplifiers, receivers, and transmitters. It was also observed from the analysis that some impacts of the space environment on the communication subsystem of any satellite, irrespective of the types, are radiation effects, extreme temperature variations, vacuum conditions, space weather, atomic oxygen, charging, and electrostatic discharge. It can be concluded from the results that the space environment has a serious impact on the communication subsystem of a satellite. These findings are relevant for satellite engineers, space sector scientists, GSM service providers, academics and communication links designers.

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