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Development and Application of a Multi-Mission TMTC-Gateway for Multi-Satellite Operation**JeongSik Choi^{a,1}, JaeHyoun Park^a, HyunChang Lee^a, SunJu Park^a, OkChul Jung^a, HyeWon Kim^a,
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Abstract

Traditional telemetry and tele-command gateways (TMTC GW) primarily supported one-to-one data communication between satellite operation systems (SOS) and cortex modems for managing telemetry (TM) and tele-command (TC) data. With the increasing number of satellites, a more efficient and automated system is required to ensure stable TM and TC management. This paper proposes a multi-mission TMTC GW that utilizes a server-client architecture based on TCP/IP to optimize resource usage. By utilizing server-client communication, the TMTC GW ensures reliable data transmission, reduced latency, and smooth connection between cortex modems and SOS. Due to this server-client architecture, the multi-mission TMTC GW deals with the limitations of traditional one-to-one communication by enabling N-to-N connections, thereby supporting more stable multi-satellite operations in simultaneous time. When it comes to the overlapping satellite passes, individual satellites can be controlled through clients of the TMTC GW, while all data, such as the event log, TM and TC, are managed centrally by the server. With this capacity, the KARI can operate stably the satellites that are currently operating and the satellites that will be launched in the future. Also, there is a backup server to prevent failure to control the satellites when the server has a problem in the server-client structure; the multi-mission TMTC GW is designed to perform satellite control using the secondary server in situations where there is a fault in the main server or the network between the server and clients is unstable. It provides a fundamental solution for managing the increasing satellite population efficiently in the New-Space era. Additionally, the proposed system provides assistance functions such as real-time data processing, error detection, and replay capabilities to enhance operational reliability. This paper discusses the architectural design of the multi-mission TMTC GW and the challenges encountered during its operation, along with the solutions developed to address these challenges.

Keywords: Ground Operation System, Satellite Operation System, Multi-Satellite Operation**Acronyms/Abbreviations**

TMTC GW	= Telemetry and Tele-command Gateways	CCSDS	= Consultative Committee for Space Data Systems
KARI	= Korea Aerospace Research Institute	SCID	= Spacecraft Identifier
SOS	= Satellite Operation System	VCID	= Virtual Channel Identifier
TM	= Telemetry	ECC	= Error Correction Code
TC	= Tele-command	RS	= Reed-Solomon
CLTU	= Command Link Transmission Unit	RT	= Real-Time
VCDU	= Virtual Channel Data Unit	PB	= Playback
CADU	= Channel Access Data Unit	TCEU	= Tele-command Encryption Unit
COP	= Communication Operation Procedure	ACK	= Acknowledgement
CRC	= Cyclic Redundancy Check		

1. Introduction

The rapid advancement of space technology, along with increasing investments from both governmental and private sectors, has led to a significant expansion of the satellite industry. Recent trends indicate a rapid increase in the number of satellites, driven by growing demands for Earth observation, telecommunications, and navigation services [1,2]. According to the advent of the New-Space movement, it has further accelerated this growth by

promoting the mass production of cost-effective, small-scale satellites and increased automation in satellite operations. Also, as the number of satellites continue to expand, the complexity of satellite operations and ground station management requests new challenges that must be addressed with innovative solutions.

Korea Aerospace Research Institute (KARI) currently operates multiple satellites, including KOMPSAT-3, KOMPSAT-3A, KOMPSAT-5, CAS500-1, and NEONSAT-1, with plans to expand its satellite populations in the coming years [3]. To manage a growing number of satellites requires handling the simultaneous overlapping satellite passes and guaranteeing stable TM and TC data communication. As the satellites increase, the conventional TMTC GWs, which support one-to-one connections between ground modems and SOS, are becoming increasingly inefficient due to the requirement for more TMTC GW software and a high operational workload [4,5]. The current system's limitations highlight the necessity of a more scalable and automated solution for efficient satellite operation.

This paper presents a multi-mission TMTC GW designed to overcome the constraints of conventional systems by introducing a server-client architecture based on TCP/IP communication. The proposed system centralizes TM and TC data management within the server while allowing clients to control individual satellites efficiently. Additionally, to enhance system reliability, a redundant server architecture has been implemented, ensuring continuous operation even in the event of a server failure or network disruption [6-8]. Moreover, the multi-mission TMTC GW automates essential functionalities, including real-time data processing, error detection, TM archiving, encryption and decryption, and automated satellite pass scheduling, significantly improving operational efficiency. This system has been successfully applied at KARI, demonstrating its capability to manage multi-satellite and overlapping satellite passes simultaneously while reducing human involvement and operational risks. The following sections provide a detailed discussion of the system's functional design, implementation, and performance evaluation.

2. Telemetry and tele-command data processing in multi-mission TMTC GW

The multi-mission TMTC GW is designed to route TM and TC data to the appropriate SOS based on spacecraft identifier (SCID). Since different satellites and antenna modems of ground station may use varying TM and TC structures and data sizes, the TMTC GW processes transfer frame header information to accurately recognize satellites and handle data format conversions, ensuring stable connections with the corresponding SOS. Additionally, the system is designed to be easily scalable. As the number of satellite increases, new frame format information can be added to accommodate additional satellites without significant modifications. This scalability feature enhances the flexibility and adaptability of the TMTC GW, making it a robust solution for managing an increasing number of satellite operations.

2.1 Telemetry processing in Multi-mission TMTC GW

As shown in Fig. 1, the satellite TM data is stored in mass memory as a N-byte virtual channel Data Unit (VCDU) [9, 10]. When transmitting TM data to a cortex modem, the satellite attaches an additional 4-byte synchronization word before the VCDU and a 32-byte Reed-Solomon (RS) code after the VCDU, forming a (N+36)-byte Channel Access Data Unit (CADU) format. When the CADU is transmitted to the KARI cortex modem, the modem removes the sync word and RS code of the CADU format and attaches a 64-byte cortex header and a 4-byte cortex tailer to the VCDU. As a result, a total of (N+68) bytes of data is transferred to the appropriate SOS through the TMTC GW. For other cortex modems, TM data is delivered in the (N+36)-byte CADU format, then the cortex header and tailer are attached, resulting in a total of (N+104) bytes being sent to the TMTC GW. The TMTC GW converts this format into a (N+68)-byte structure in order to support the SOS in processing the TM data.

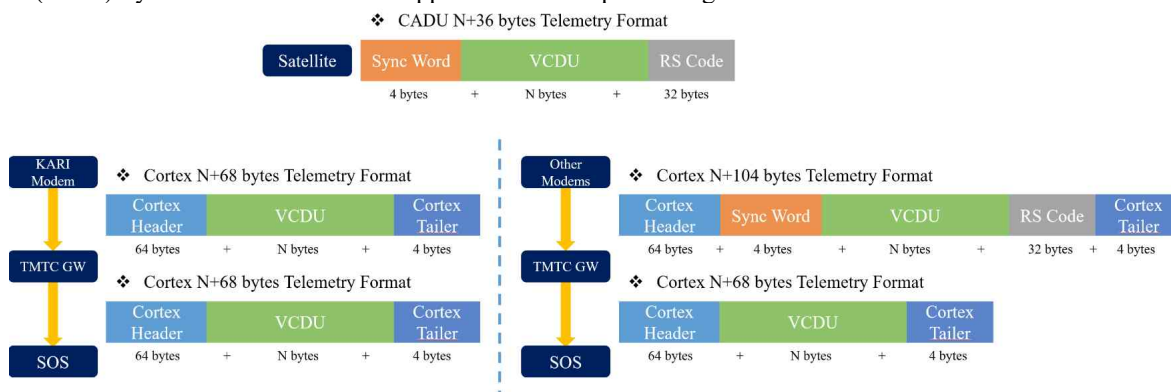


Fig. 1. Telemetry format of KOMPSAT and CAS500 series

Likewise shown in Fig. 2, the TM data for NEONSAT-01 is stored in a $(N+2)$ -byte VCDU format. To ensure 4-byte alignment for transmission to both KARI and other modems, a 2-byte cortex fill is added, resulting in a total of $((N+2)+2)$ bytes. For KARI cortex modems, this VCDU is appended with a cortex header and tailer, creating a $((N+2)+70)$ -byte data package that is delivered to the TMTC GW. The TMTC GW then forwards this data to the appropriate SOS. For other cortex modems, the VCDU is combined with a 4-byte sync word and a 32-byte RS code, forming a $((N+2)+36)$ -byte CADU. A cortex header and are subsequently added, resulting in a total of $((N+2)+106)$ bytes sent to the TMTC GW. The TMTC GW processes this data, converting it into a $((N+2)+70)$ -byte format before transmitting it to the designated SOS.

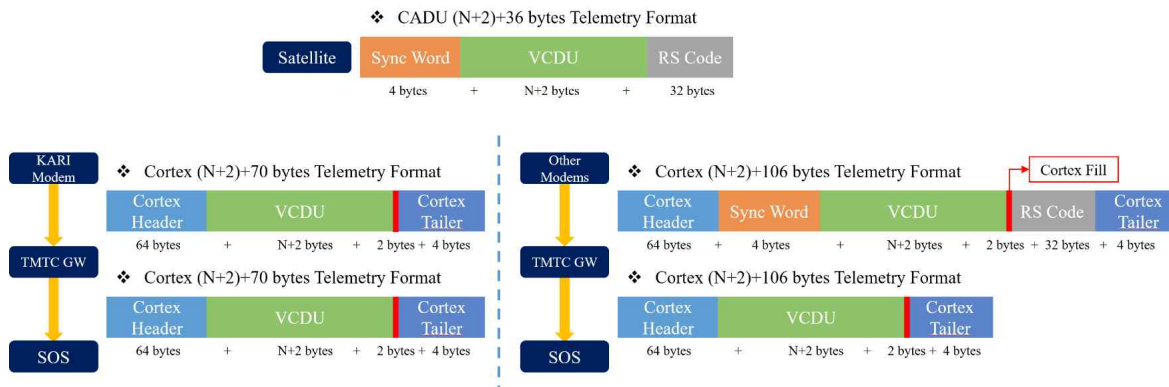


Fig. 2. Telemetry format of NEONSAT Series

The multi-mission TMTC GW efficiently handle TM data from multiple satellites, ensuring data integrity and operational reliability. It performs RS decoding to detect and correct errors, maintaining accurate TM despite transmission noise or interference. Additionally, it uses de-randomization to restore the original data sequence, ensuring compatibility with the SOS. This function ensures that the SOS can correctly interpret the received TM data. The TMTC GW also generates TM and event logs, which provide detailed records of TM reception and system events, including anomalies and errors. These logs support error analysis and troubleshooting, by allowing operators to trace the root cause of issues and implement corrective actions.

The multi-mission TMTC GW is designed with scalability to support future satellite missions that may use different TM formats compared to existing satellites. Its flexible data processing architecture allows it to standardize and convert diverse TM formats, ensuring that even unconventional TM structures can be recognized and processed by the SOS. This adaptability eliminates the need for significant changes to the existing system, maintaining compatibility across various satellite missions. By efficiently managing both traditional and new TM formats, the multi-mission TMTC GW enhances TM data handling and operational efficiency in multi-satellite missions.

On the other hand, when it comes to choosing the TM mode, the satellite's status data is categorized into real-time (RT) mode and playback mode (PB) based on transmission timing and data storage method. When a link is established between the ground station and the satellite, a request message from the TMTC GW can be used to receive either RT or PB data individually or both simultaneously, allowing the monitoring of the satellite's status.

2.2 Tele-command processing in Multi-mission TMTC GW

All of the satellites operated in KARI, currently following the international Consultative Committee for Space Data Systems (CCSDS) standards by performing the communication operation procedure (COP). The multi-mission TMTC GW can be used fluidly because it can be set on/off depending on whether the antenna modem performs COP functions. COP ensures data integrity and prevents errors when TC data is transmitted from the cortex modem to the satellite. It helps to avoid data distortion, loss, and duplication during transmission, while also detecting and correcting bit errors that may occur in the communication process. By doing so, COP guarantees the accurate delivery and proper execution of commands on the satellite. Before the COP is performed, the raw command that is created in SOS consists of a X-byte transfer frame header, a Y-byte packet header, and command frames. The transfer frame header contains information about the satellite, virtual channel, and command frame to which the command is transmitted, such as SCID, virtual channel identifier (VCID), frame length, and so on. The packet header has information, such as application identifier, sequence flag, sequence count, and packet length. And the command

frame has a 10-byte command frame header, a less than 244-byte command data field, and a 2-byte cyclic redundancy check (CRC).

Through COP, likewise shown in Fig. 3, a 2-byte start sequence to indicate the beginning of the command and an A-byte codeblock and a 1-byte error correction code (ECC) are repeatedly generated [10]. A single CLTU consists of up to 123 codeblocks, with each codeblock dividing the transfer frame header, packet header, and command frame into A-byte segments for transmission to the satellite. Finally, a tail sequence is added to complete the command link transmission unit (CLTU) format that the satellite can recognize. The multi-mission TMTC GW performs this COP function and converts commands generated by the SOS into a CLTU format that the satellite can receive. In addition, for the COP processed commands, the multi-mission TMTC GW can be turned off this function by the operator. Moreover, TMTC GW has improved the security of TC transmission by supporting encoding and randomization functions, enabling secure communication from external factors.

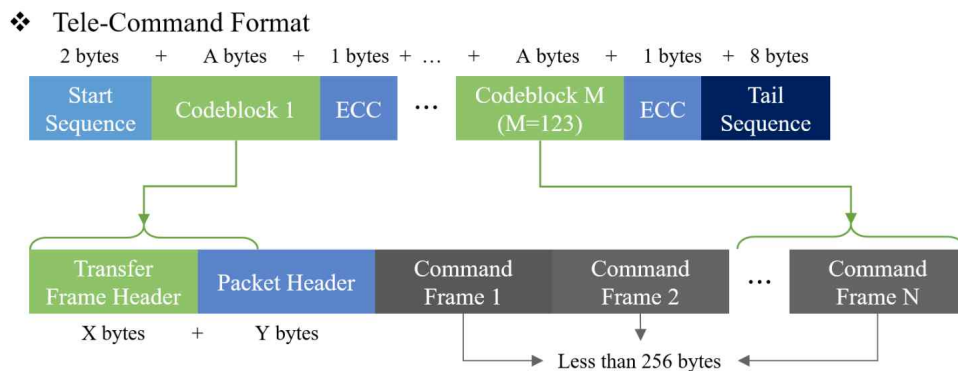


Fig. 3. CCSDS Command Format

3. Functional overview of the multi-mission TMTC Gateway

The multi-mission TMTC GW is designed to overcome the limitations of traditional one-to-one communication systems and efficiently manage TM and TC data for multiple satellites. By utilizing a server-client architecture and implementing advanced data standardization and automation features, the system enhances operational efficiency, scalability, and reliability. Furthermore, the implementation of automation and additional convenient functions for the simultaneous management of multiple satellites requires the establishment of a stable and systematic data processing framework. This paper presents a structured flow chart for handling TM and TC by visualizing and organizing appropriate processing flows for each data type. Through this approach, the TMTC GW is designed to identify errors, generate alerts, and manage the overall satellite communication process, ensuring efficient transmission, reception, and processing of TM and TC data.

Figs. 4 (a) is schematically illustrate flow charts for the TM processing procedures. In the case of TM, the multi-mission TMTC GW first verifies the IP address of the SOS and compares the satellite type in the SOS with the pass plan to ensure the match. When an error is detected in this process, the connection with the SOS is terminated. And the results match, the SOS is automatically connected to the TMTC GW to prepare for TM reception. Simultaneously while the SOS connection process, the TMTC GW verifies the designated antenna and satellite information from the pass plan before the satellite pass begins. Based on this information, the system sends a connection request to the appropriate cortex modem. After the connection is successfully established, the TMTC GW verifies the satellite type configured in the SOS. And the type matches, a request message is transmitted to the modem, starting the TM reception process. Once the pass is completed, all connections are automatically released, and preparations for the next satellite pass begin.

Figs. 4 (b) is schematically illustrate flow charts for the TC processing procedures. When transmitting TC, the TMTC GW first verifies the IP address of the connected SOS, likewise for TM. And then analyzes the SCID of the received data and compares the satellite type in the pass plan with the type registered in the SOS. If the results match, the TMTC GW applies encryption and security processing to the TC data before transmitting it to the modem. At the same time, while establishing the SOS connections, the TMTC GW checks the antenna modem and satellite information based on the pass plan and sends a connection request to the appropriate system. Once the connection is successfully established, it compares this information with the SOS settings. If they match, the TC data is transmitted. After the modem sends the TC to the satellite, it returns an acknowledgement (ACK) to the TMTC GW. The TMTC GW processes this ACK and relays it to the SOS. Once the SCID is analyzed during the initial transmission, a

routing path is established, allowing continuous TC transmission without further SCID verification. With this structured system, the TMTC GW ensures fast and accurate TM and TC communication with the satellite.

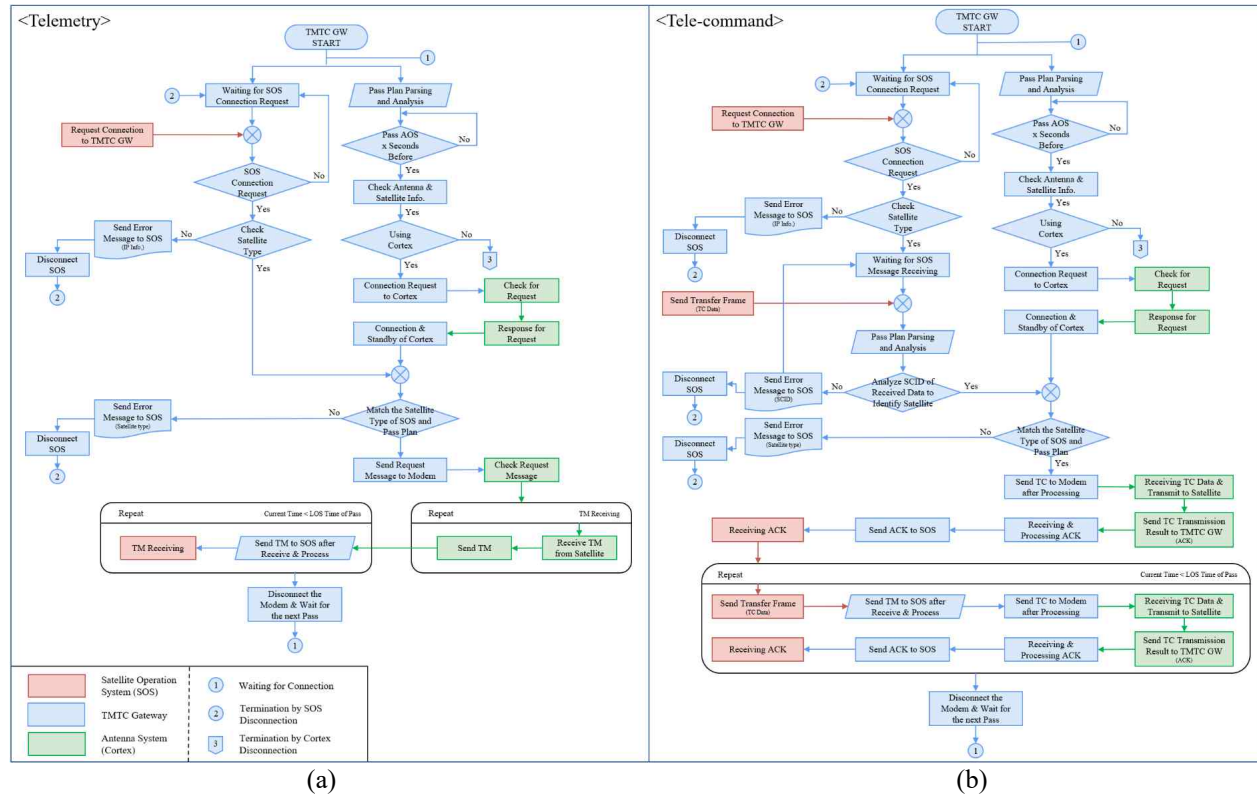


Fig. 4. Process flow chart of the TMTC GW
(a) Telemetry, (b) Tele-command

3.1 Data standardization, real-time processing, and security

The multi-mission TMTC GW standardizes various TM and TC data formats that differ in size and structure depending on the satellite and connects them to the Cortex modem. This standardization enables consistent data transmission across SOSs, facilitates seamless system integration, and reduces the complexity of multi-satellite operations. Furthermore, standardizing data formats is a crucial function for managing the increasing number of satellites and ensuring scalability when integrating new types of satellites into the system. As illustrated in Fig. 6, the system performs functions such as RS decoding, de-randomization, COP processing, and randomization, which contribute to error detection and data reliability improvement of standardized data.

Additionally, the TMTC GW provides a real-time display of TM and TC transmission status, allowing operators to quickly detect anomalies and make prompt decisions during satellite operations. This real-time processing capability ensures accurate satellite status monitoring, facilitates problem identification and resolution, and ultimately enhances mission success rates.

The SOS systems communicating with satellites are connected to the Cortex modem through the TMTC GW. The TMTC GW is designed to allow access only from pre-approved IP addresses within KARI’s internal network via a firewall, making unauthorized access highly challenging. Furthermore, since all external connections are established through the TMTC GW, any unauthorized access attempts can be mitigated by isolating the TMTC GW, thereby safeguarding the entire system. Additionally, the system continuously monitors and logs input, output, and event data in real-time, enabling early detection and proactive response to potential security threats.

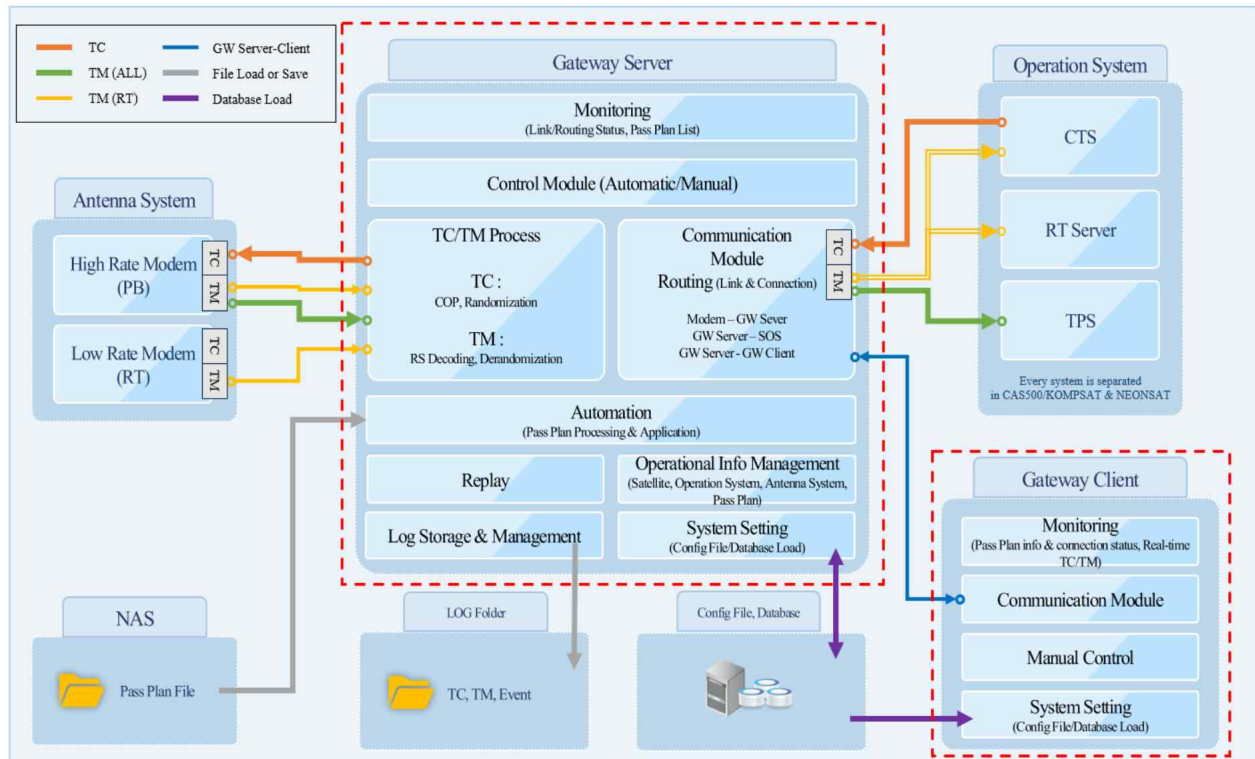


Fig. 5. Block diagram of multi-mission TMTC GW

3.2 Replay and archiving

Likewise in the Fig 5, the TMTC GW includes advanced replay functions, enabling operators to review historical TM data for post-mission analysis, anomaly investigation, and performance assessment. This function enhances the ability to evaluate mission outcomes and identify causes of operational issues, supporting continuous improvement in satellite management. Additionally, the multi-mission TMTC GW provides data archiving to store and retrieve TM/TC logs between cortex modems and TMTC GW, TM/TC logs between SOS and TMTC GW, and the event logs while this system is working. This archiving assists TM or TC in identifying where the problem occurred and helps them view records of events that occurred during the satellite pass, improving operational stability and efficiency. Furthermore, the archived event logs are to enable efficient troubleshooting and response in the event of operational problems.

3.3 Automated connection and multi-satellite operations

For efficient satellite operations, the KARI systematically manages satellite pass information through a pass plan. This plan includes key parameters such as ground station allocation, antenna selection, pass duration, and maximum elevation angle, allowing for organized and optimized satellite tracking and communication. The system automates satellite communication using stored satellite pass plans, enabling automated satellite-to-cortex modem connections. This automation minimizes manual intervention, reducing the risk of human errors and improving overall operational efficiency. The TMTC GW supports N-to-N communication by using a server-client architecture, which allows simultaneous management of multiple satellites without the need for dedicated hardware for each satellite. This architecture optimizes resource allocation and data routing, maximizing resource utilization while minimizing operational complexity. Performance tests at the KARI demonstrated the TMTC GW’s capability to manage all the satellites that are currently operating and will be launched in the future at once. This multi-satellite management capability enhances operational productivity and mission flexibility, making it a robust solution for growing satellite constellations.

3.4 Server dualization

To ensure system reliability and uninterrupted operations, the TMTC GW is designed with redundant servers at Jeju and Daejeon control rooms. During normal operations, all clients connect to the primary server. However, as

shown in Fig. 6, if network disruptions or server failures occur, the system automatically switches to local server or backup servers, maintaining continuous mission control. This redundancy mechanism minimizes downtime and prevents data loss, ensuring mission continuity and data integrity even in unexpected situations. Additionally, the scalable server-client architecture supports future satellite growth, providing a flexible and adaptable solution for managing increasing satellite populations in the NewSpace era. By implementing automation and redundancy, the TMTC GW reduces human intervention and minimizes human errors, thereby enhancing operational stability and efficiency. The system’s scalable and reliable design ensures effective satellite communication and management, supporting complex satellite operations in modern space missions.

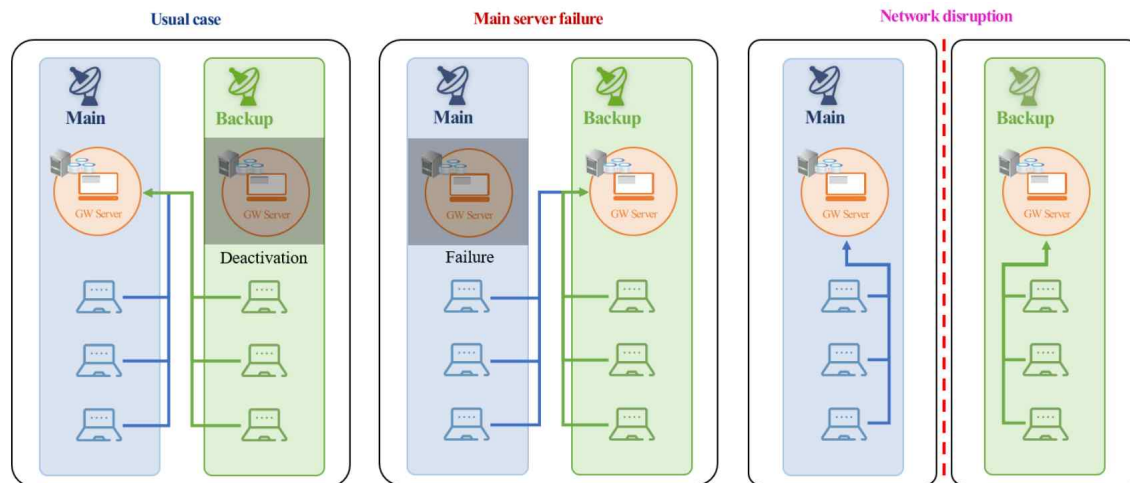


Fig. 6. Structures of server dualization

3.5 Routing for multi-connection

During the operation of satellites using the multi-mission TMTC GW, one issue is identified in TC transmission and another in TM reception. For TC transmission, commands are encrypted using the tele-command encryption unit (TCEU) before being sent to the satellite. Depending on the satellite operation method, cases may arise where encryption of the transfer frame header is required for higher security classifications. However, the SCID of the satellite, which is placed in the transfer frame header, is also encrypted during this process, causing the TMTC GW to fail in establishing the appropriate routing to the cortex modem. To solve this issue, the solution utilized the fact that the multi-mission TMTC GW forms the routing path with the first command sent. Therefore, for satellites with high-security classifications where the transfer frame header is encrypted, the TMTC GW initially sends the control packet to establish routing without encryption. Once the routing is established, encryption is enabled to proceed with actual command transmission and mission execution. During the routing establishment process, only control packets are transmitted to the TMTC GW, ensuring that no information is leaked externally. This enhances security and enables stable operation from a security perspective.

The current TM reception architecture operated by KARI consists of multiple clients connected to the TMTC GW Server, where TM data processed by each client is aggregated and forwarded to the appropriate SOS. To ensure the proper routing of this data, an effective routing mechanism is required, with the most common approach being the parsing of the transfer frame header to identify the satellite using its SCID. However, in multi-overlapping pass scenarios, an excessive influx of data can cause performance bottlenecks due to the time-consuming process of checking the SCID for each frame. Furthermore, errors in SCID parsing may prevent TM data from being delivered to the designated SOS, or in more severe cases, may result in disruptions to SOS software functionality.

Previously, IP-based routing was used to mitigate such issues by forming direct connections between each SOS and the system. However, since the TMTC GW transmits all TM data from a centralized server, it is not feasible to distinguish individual satellites based solely on IP addresses. To address this limitation, the TMTC GW adopts a routing table-based approach, where each satellite is assigned a dedicated port, enabling controlled connections. This method eliminates the need to verify the SCID for every frame, allowing for faster and more accurate TM transmission to the designated SOS. Additionally, by applying this port-based routing approach, the multi-mission TMTC GW effectively resolves errors in TM data transmission without requiring modifications to the existing SOS

architecture. This guarantees that the original system configuration is maintained while enabling precise and efficient data routing.

Table 1. Simplified routing table for mapping the satellites and ports

Satellite	TMTC GW server IP Address	Port	Destination
K3	xxx.xxx.xxx.xxx	0001	TM Server IP 1
K3A	xxx.xxx.xxx.xxx	0002	TM Server IP 1
K5	xxx.xxx.xxx.xxx	0003	TM Server IP 1
C1	xxx.xxx.xxx.xxx	0004	TM Server IP 2
N01	xxx.xxx.xxx.xxx	0005	TM Server IP 2

* Every TMTC GW server IP address is the same.

Furthermore, in previous satellite operations at KARI, a single RT Server is sufficient for managing TM data. However, as the number of satellites increases, concentrating all data on a single RT Server may lead to system degradation and performance issues, making congestion control essential. To address this, the multi-mission TMTC GW dynamically configures routing paths to distribute TM transmissions across multiple servers, such as RT Server1 and RT Server2, when overlapping satellite passes are scheduled. This approach optimizes data processing efficiency, enabling faster handling of large volumes of data, including imagery and TM, through an effective congestion control mechanism.

5. Conclusions

The proposed multi-mission TMTC GW effectively addresses the challenges posed by the increasing number of satellites by implementing an automated and scalable communication framework. Unlike traditional one-to-one satellite operation systems, which require direct connections between the SOS and ground station modems, the multi-mission TMTC GW introduces an N-to-N connection architecture, significantly enhancing operational efficiency. Through its server-client structure, the GW enables simultaneous control of multiple satellites while optimizing resource allocation and minimizing human intervention. One of the major advantages of the system is its ability to standardize diverse TM and TC data formats, ensuring compatibility across different ground systems and satellites. This standardization is crucial for maintaining data integrity and operational scalability as new satellite models are integrated into existing systems. Additionally, real-time monitoring features facilitate the immediate detection of anomalies, allowing operators to swiftly diagnose and resolve issues, thereby improving mission success rates.

Security measures have also been reinforced within the TMTC GW, with access strictly controlled through predefined IP addresses and firewall configurations. By centralizing all external connections, unauthorized access attempts can be effectively modified, ensuring the stability of the overall satellite communication network. Furthermore, continuous logging and event monitoring enable proactive threat detection and response, strengthening the security of the system.

To overcome operational challenges, the TMTC GW implements innovative solutions such as pre-routing commands for TC transmission and port-based routing for TM data distribution. By establishing dedicated ports for each satellite, the system eliminates the need for frame-by-frame SCID verification, reducing processing overhead and improving transmission efficiency. This approach prevents data congestion and ensures that data is accurately delivered to the corresponding SOS without requiring major modifications to existing software. In practical applications at the KARI, the system has demonstrated its ability to manage multi-satellite and overlapping satellite passes efficiently. By leveraging automated connections, error detection mechanisms, and redundant server architecture, the TMTC GW provides a robust and future-proof framework for satellite operations. As the satellite population continues to expand in the New-Space era, the multi-mission TMTC GW offers a scalable, secure, and efficient solution for ensuring the seamless operation of multiple satellites.

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