Information Flow Design and Verification for Networked Satellite Systems

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Abstract. For efficient information sharing and timely processing, networked satellite constellation with the feature of space and terrestrial network integration will be constructed. Information flow design and verification is necessary for networked satellites with complex information interfaces. This paper describes and analyzes information feature classification, information flow based network architecture design, and information flow functionality validation and performance evaluation for networked satellite systems. We also propose design strategy analysis of information transmission, processing and storage as reference and suggestion. Furthermore, an instance of information flow performance evaluation is introduced.

Keywords: Networked satellite · Information flow · Network architecture

1 Introduction

Along with Space-Ground integrated development, networked satellite systems will be of great benefit to efficient sharing and integrated processing of space information, also to promoting system service quality, expanding service area and exploring user requirement. For instance, navigation satellite constellation with multi-interface to ground and space has multiform information and complex information transmission routes involved with system-system, satellite-satellite and equipment-equipment information interaction [1–3]. Telecommunication satellite and remote sensing satellite systems have similar characteristics. Information flow integrated design and verification is necessary for networked satellite systems. Based on demand analysis of networked satellite systems, compatibility and interoperability across the network should be considered in the architecture design, which are beneficial to terrestrial users and application efficiency.

We study on information flow integrated design towards the application background of networked satellite systems. This paper proposes several design guidelines and key elements. Based on functionality operation analysis of information type, quantity, transmission and processing, communication channel planning, information feature classification, network architecture design and information flow evaluation are conducted.

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The remainder of the paper is structured as follows. Section 2 presents networked satellite system information classification. In Sect. 3, we describe information flow network architecture design. The analysis of information flow functionality validation and performance evaluation is presented in Sect. 4. Section 5 introduces an instance of information flow performance evaluation. We conclude in Sect. 6.

2 Networked Satellite System Information Classification

2.1 Information Classification

Information classification based on functionality, purpose and characteristics is useful for designing corresponding information transport and process strategy towards multiplex requirements.

Information classification based on functionality and purpose:

- Control information includes telecommand, operating parameters, constellation network configuration data and on-orbit reconfiguration data.
- Monitor information includes telemetry, anomaly data, command response, attitude data, space environment measurement data, dynamic environment measurement data and memory download data.
- Operation information includes data generated by satellite payloads.

Information classification based on characteristics:

- Periodicity data can be modelled by periodic function. For instance, satellite equipment health monitoring data are generally collected with fixed cycle.
- Stochastic data can be modelled by stochastic process. For instance, satellite command response and fault data are triggered by specific event randomly.

Based on information characteristics analysis, fusion-model can be constructed for information flow design simulation.

2.2 Transmission Channel

Networked satellite system information interactive transmission is based on Ground-Satellite Link (GSL) and Inter-Satellite Link (ISL). Furthermore, ISL is one of the symbols of networked satellite system [4].

- Wireless communications and measurements between satellite and terrestrial station are supported by GSLs for satellite control, monitor and data transport. GSLs upload commands for satellite operating, and download telemetry and payload data for health monitoring and data collection.
- Wireless communications and measurements between satellite and satellite are supported by ISLs for satellite control, monitor and data transport of invisible satellite, also for inter-satellite ranging and time synchronization.

3 Information Flow Based Network Architecture Design

3.1 Network Architecture Design Elements

Several design elements should be considered for information flow based architecture design as followed.

- **Reliability.** Design to guarantee normal or degraded running when failure occurs. Based on distributed information flow network with multi-controller, information processing centre can be alternate in particular situation to insure information management basically. Redundant information transport channels and equipment are adopted both on-board and externally. Isolation and redundancy of information node shared parts are adopted to avoid single-point failure. Information interface switch is supported for redundancy. Appropriate margin of information network capacity and bandwidth are reserved to avoid congestion.
- **Safety.** Design to avoid local breakdown for system safety. Information sources which affect safety should be identified. Safety of storage and process of important information sources should be enhanced with distributed redundancy. Important control commands should be multi-level authenticated to avoid abnormal execution. Appropriate selection strategy should be adopted to avoid information competition when multiple information flow channels link to node.
- **Efficiency.** Design to promote information management efficiency based on reliability and safety. Information management resources should be allocated and scheduled with trade-off among reliability, safety and efficiency. Equipment hardware and software and information coupling should be reduced for simplified system scheme. Layered-network architecture should be designed to reduce network complexity, also for flexibility. Standard or validated products should be selected for maturity.

3.2 Information System Architecture Design

Distributed and composite architecture is designed for networked satellite information system generally, for graded process in system, sub-system, equipment and assembly, also reduce information flow complexity. Master node is always the system-mission computer. Slave node is always the intelligent processing unit which has single functionality. Slave node can be designed for updating as master node due to management. Satellite information system information flow network backbone structure is generally based on the on-board data bus. Information flows in the on-board data bus.

An instance of layered information system architecture is shown in Fig. 1, which consists of information processing layer, digital signal processing layer, signal preprocessing layer and antenna layer. Information always flows in the upper layer while signals always transmit in the lower layers.

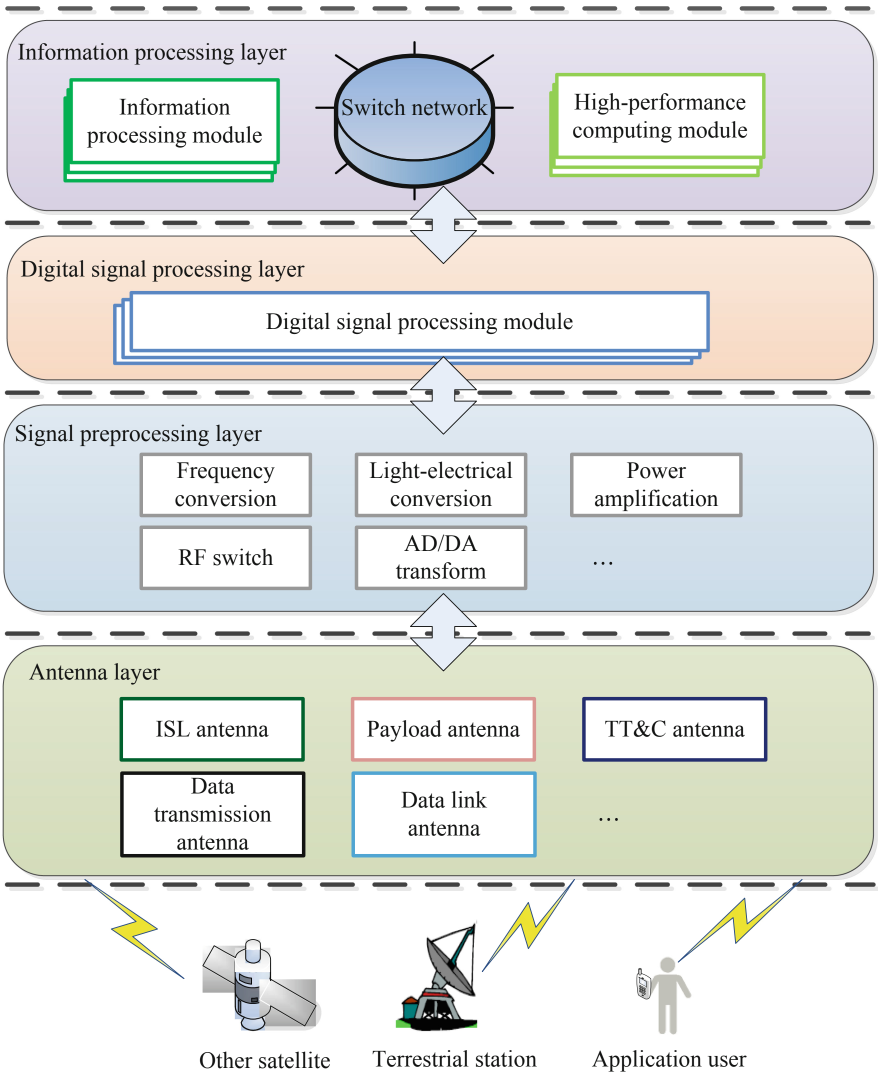

Fig. 1. Block diagram of layered information system architecture

With the improvement of on-board computing power, storage capacity, and space communication capabilities, networked satellite system based on integrated space-terrestrial routing could be introduced in the future. Considering compatibility with terrestrial IP networks, the network layer of satellite information system architecture should involve IP. Figure 2 shows an instance of Ethernet-based information system architecture with switching network linked by on-board equipment, which has great flexibility.

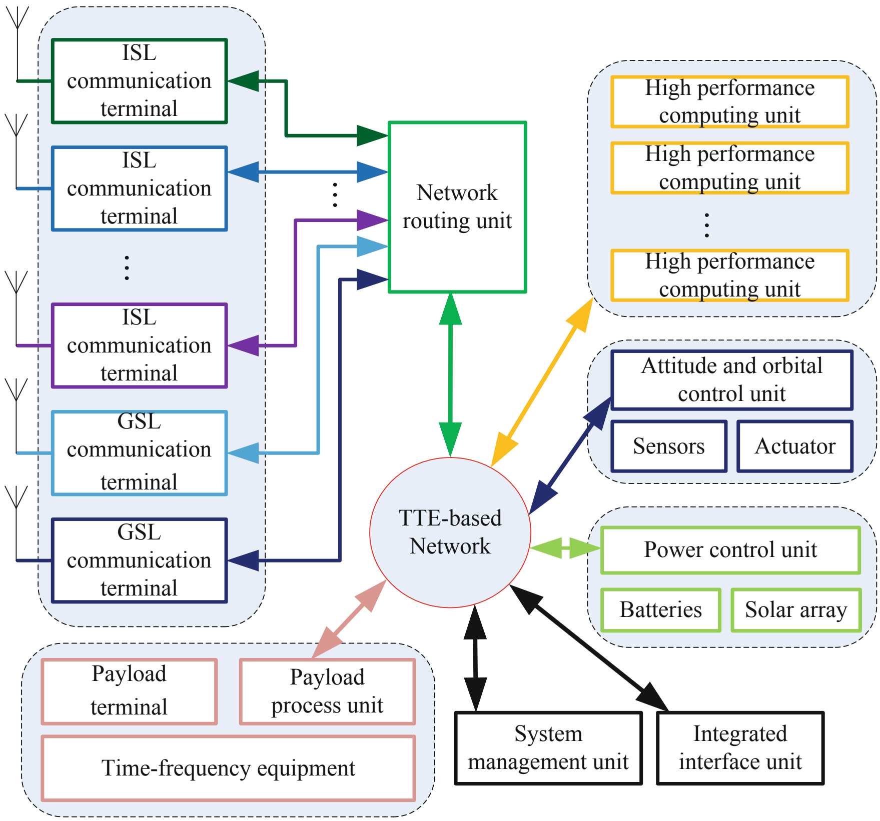

Fig. 2. Ethernet-based information system architecture

Time Triggered Ethernet is adopted to support time-triggered services to solve the problem that traditional Ethernet is difficult to guarantee the time certainty of satellite information system. The switch with redundant backup is the core of the information system, and each satellite device is connected to the corresponding port of the switch. The quantity of ports and switches can be expanded corresponding to the number of nodes accessing the network with extensibility. The information system task can be assigned by each node with flexible and adaptable configuration, which is beneficial to realize system-level resource dynamic management and reconstruction.

3.3 Information Transport and Process Strategy

Information Flow Network Protocol. Information flow network architecture should be layered to reduce the coupling between layers with standard protocols.

Application layer protocol should be designed according to the specific task. Transport layer, network layer, data link layer, physical layer protocol should refer to the relevant standard design or implementation. For the data types that require high reliability of information transmission, such as telecommand data and operation control data, reliable data transfer services with standardized definition should be provided.

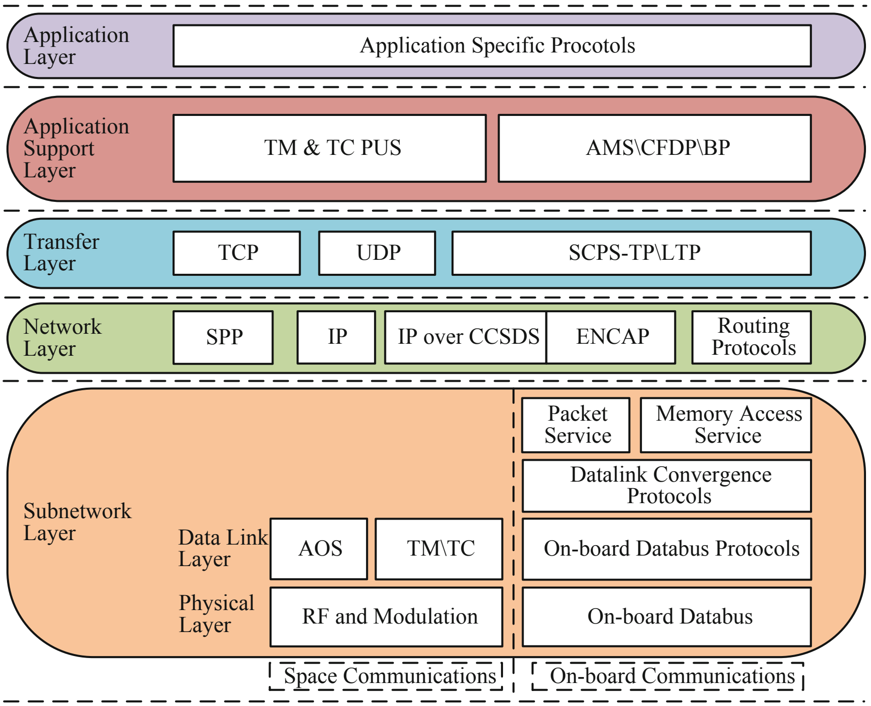

Fig. 3. CCSDS-based network protocol architecture

GSL and ISL information flow protocols should be designed with consideration of compatibility and interoperability, technology evolution to support ground segment and space segment constellation seamless transmission of information across the network. The system should provide unified control interface for terrestrial users, simplify the format conversion between ground and space, also reduce the handling complexity of terrestrial users, and improve the efficiency. Figure 3 shows an instance of CCSDS-based network protocol architecture [5].

Information Flow Integrated Application. Based on information sharing in the satellite information flow network, system functions, performance, reliability and safety can be improved. For instance, energy, thermal, attitude, orbit and other key feature data shared for integrated application. Interactive support for transmission should be provided in multiple information flow channels.

Information Flow Scheduling. Several design guidelines of information flow scheduling are proposed generally to ensure the processing logic among network nodes.

- The sequence of response events of information flow in each node should meet the design logic requirements.
- Scheduling relationships should be adapted to the performance changes of communication interfaces over the full life cycle of the satellite.
- When any information flow node interfaces changes, the information flow matching test should be performed.
- Based on the premise of meeting the functional and performance requirements, simplification of the scheduling is important.

In particular, satellite-time information flows require targeted design. For instance, time synchronization of satellite and ground, time synchronization of satellite equipment should consider the starting point of time, time synchronization accuracy, time calibration, time information transmission delay.

The delay characteristics are defined as follows, and the total delay T is calculated by Eq. (1).

$$T = t_{\mathrm{s}} + t_{\mathrm{t}} + t_{\mathrm{p}} + t_{\mathrm{q}} \tag{1}$$

- t_{s} is the time required for the device to send a data frame from the first bit of the frame sent until the last bit of the frame is sent.
- t_{t} is the time takes for a signal to propagate a certain distance through a channel. Due to the short propagation distance of satellite internal signal, the propagation delay is negligible generally. For ISL and GSL, the propagation delay need to be included.
- t_{p} is processing delay after the device receives data.
- t_{q} is the time occupied for data in the device's input queue and output queue waiting for processing.

4 Information Flow Functionality Validation and Performance Evaluation

After functional validation and performance evaluation, information flow design results can be optimized by comparing with the design requirements and iterative design.

4.1 Information Flow Evaluation

Information flow evaluation indicators include completeness, accuracy, and timeliness.

- Completeness represents that the difference between the design result and the real situation of object types, quantities and parameter range in the information flow.
- Accuracy indicates the difference between the parameter value and the actual value of the objects in the information flow.
- Timeliness represents that the length of time of information flow generation, transmission and processing.

From the perspective of information flow network, for network managers and users, technical indicators that evaluate the performance of information flow network include throughput, capacity, bandwidth utilization, response time, delay, etc.

4.2 Information Flow Simulation

Through mathematical and semi-physical modeling, simulation and analysis of information flow design should be implemented by software and sample data, which could provide the basis for the information flow design and improvement. Information flow simulation generally covers all kinds of information flow channel function, analysis of the actual capacity of information flow network, obtain information system performance evaluation result. It can also cover untestable projects in information flow design or verify high-cost items, examine multiple information paths, multiple simultaneous events, etc.

4.3 Information Flow Test

The main purpose of information flow test is to inspect the satellite information transmission process. Through checking and solving the problems, the test should verify that the information flow network operation meets satellite design and application requirements, which ensures correct function, system coordination and qualified performance parameters.

Information flow test should generally be included in the equipment, sub-system, system tests and special tests level by level. The main purpose of information flow test includes:

- Verify the correctness, consistency and adaptation of the satellite information flow design.
- Check the correctness and adaptation of the satellite information network nodes.
- Verify the correctness and adaptation of the satellite external information interface.

5 Instance of Information Flow Performance Evaluation

The BDS-3 space constellation is chosen as the evaluation object. The basic constellation consists of 3 GEO satellites, 3 IGSO satellites, and 24 MEO satellites [6]. Based on the assumption that the semiduplex ISLs rate is 100kbps with CCSDS AOS protocol data frame [7, 8], the information flow performance evaluations which include network throughput and bandwidth utilization are presented. Different information types are simulated including control information, monitor information, and operation information with periodicity or stochastic characteristics, which flow in the network.

Figure 4 shows the total throughput of the network. Throughput is defined as: the amount of data successfully transmitted in a unit of time [9].

T_i is the throughput of satellite No.i, Calculate the total throughput of the network as:

$$T = \sum_{i=1}^{30} T_i \tag{2}$$

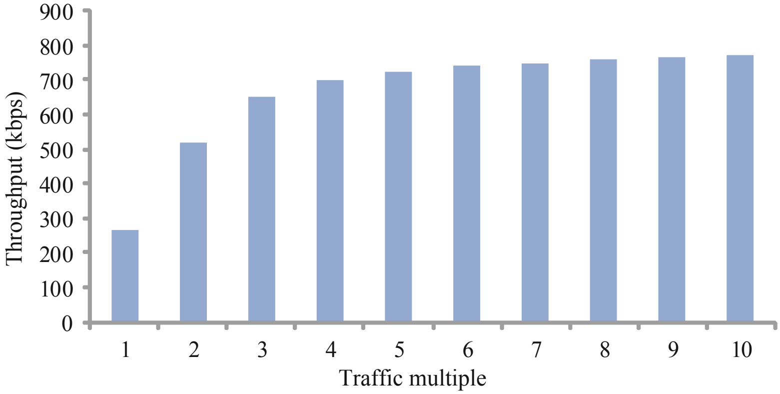

Fig. 4. Total throughput evaluation

Along with the information traffic increases, the value of the network throughput increases. When the information traffic increases to six times the initial value, the network throughput increases very little, this could be considered as the maximum network throughput.

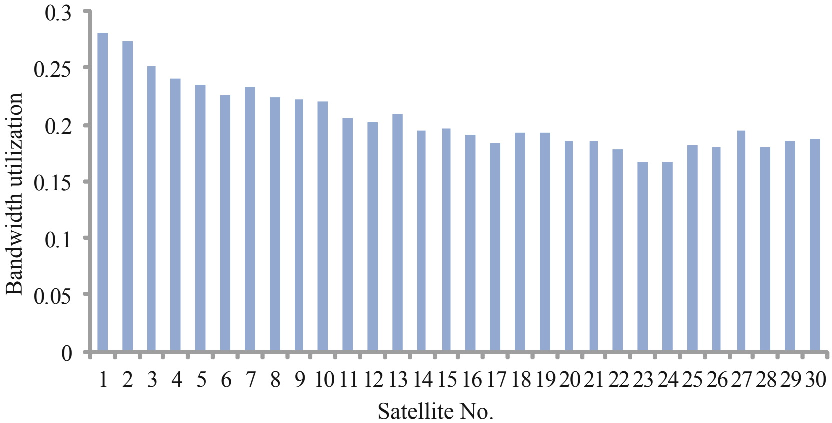

Fig. 5. Bandwidth utilization evaluation

Figure 5 shows the bandwidth utilization of 30 satellite nodes in the network. Bandwidth utilization is defined as: Link layer effective transmission bandwidth divided by Total bandwidth [10].

η_i is the bandwidth utilization of satellite No.i, Calculate the average bandwidth utilization as:

$$\overline{\eta} = \frac{\sum_{i=1}^{30} \eta_i}{30} \approx 0.206 \quad (3)$$

For demonstration, the results are reasonable due to the vacant bandwidth which is not occupied by the default setting of information traffic.

6 Conclusion

This paper studies on networked satellite information flow integrated design and verification with instance of evaluation for reliability, maturity and accuracy to guarantee stable and efficient operation of networked satellite systems. With the advancing Space-Ground integrated development, the connotation and extension of networked satellite system information flow design will be further expanded.

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