Design of a Spacecraft Network System Based on Space-Ground Integrated Network

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Abstract. Since the rapid development of the internet technology, the space-ground integrated network is becoming an inevitable trend of development in communication between space and ground. At present, the internet technology to realize the integrated communication has been applied to ground stations. Similarly, the internet technology can be used in the communication system of spacecraft. But comparing to the network used on the ground, the space-link between the spacecraft and ground stations has different characteristics, such as the high propagation delay, the narrow bandwidth, the asymmetry transmission speed of the bidirectional space-link and the complicated Electromagnetic Compatibility (EMC) environment in the spacecraft. These can make the space-ground integrated network to be inefficient and unreliable. To resolve these problems, an efficient and reliable space network system for the spacecraft is designed based on the space Ethernet switch and the space-ground gateway. And the error-control mechanism of application layer, the IP package partition strategy of data link layer and the cable layout method of physical layer has been proposed to optimize the TCP/IP protocols used in the ground. The spacecraft network system can be used in the space-ground integrated network of GEO, MEO or LEO spacecraft and the deep space exploration.

Keywords: Space-ground integrated network · Spacecraft · Efficient and reliable · Network system

1 Introduction

With the development of network technology, the integrated network between space and ground becomes the inevitable development trend. At present, the ground TT & C communication system has realized the integrated communication based on network, while the communication inside the spacecraft is still based on the bus or point-to-point communication. If the information exchange between the internal equipment of the spacecraft adopts network to realize the integrated communication with the ground network, the communication protocol can be unified, and the communication efficiency can be improved. At present, the integrated communication based on network is mainly in the theoretical stage [1–5], and its engineering application is less. The international space station has used the network for the high-speed transmission of experiment data, and carried out on orbit tests, but it has not been applied to the data transmission task of spacecraft platform.

In order to realize the integrated network communication between spacecraft and ground, it is necessary to apply ground network technology to the spacecraft TT & C communication system. Compared with the ground network environment, the space-link of spacecraft has the characteristics of long-time delay, limited bandwidth, unbalanced bandwidth of bidirectional space-link and complex electromagnetic environment inside the spacecraft. The direct application of ground network technology will lead to problems of low communication efficiency and poor reliability for the integrated space-ground network. In view of the above problems, this paper puts forward a solution of space network system to achieve efficient and reliable integration of space-ground network communication.

2   Architecture of Spacecraft Network

With the rapid development and wide application of Ethernet technology, the integration technology of space communication and ground network has become the main development trend in the future. The proposed draft of red book [6] provides guidance for the implementation of IP packet transmission over CCSDS space data link protocol between spacecraft and ground system, so that the communication between space and ground can start from the network layer to adopt consistent protocol to realize integrated network communication, and establish an integrated network communication system between space and ground.
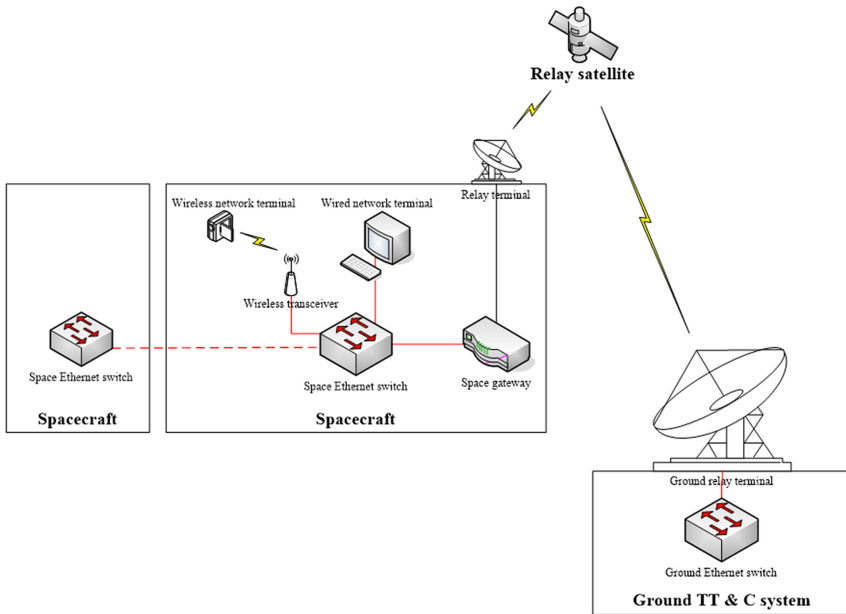

Fig. 1. Architecture of space-ground integrated network system

Through the analysis of Ethernet technology and IP over CCSDS protocol in space application to construct the space-ground integrated network system architecture based on space Ethernet switch, wireless transceiver equipment and space-ground gateway, it can support the wired or wireless access of self-developed or commercial network terminal, the communication between different spacecraft, and the space-ground integrated network communication through relay satellite system. The system architecture is shown in Fig. 1.

1. The space Ethernet switch is responsible for the access of wired network terminals and networking between different spacecraft. It supports the standard Ethernet protocol and interface, and exchanges the data of network terminals inside the spacecraft with other spacecraft network terminals and the space gateway.
2. The wireless transceiver is responsible for the access of the wireless network terminal. It supports WIFI protocol and connects the data of the wireless network terminal to the space Ethernet switch to realize the conversion between the wireless network protocol and the Ethernet protocol. It also can exchange data with other spacecraft network terminals and the space gateway through the space Ethernet switch.
3. The space gateway is responsible for the bidirectional space-link data transmission between the spacecraft network and the ground network. It transforms the IP protocol of the space network [7] and the CCSDS AOS space link transmission protocol [8], completes the mapping between the spacecraft network and the ground network protocol, and realizes the gateway function of the integrated space network [9].

3   Protocol Stack of Spacecraft Network

Aiming at the limitation of long-time delay, limited bandwidth and inconsistent rate of bidirectional space-link, the multi-layer network protocol is optimized, which effectively reduces the conversion link of space protocol, and improves the efficiency and reliability of space-ground integrated network.

The network protocol stack of spacecraft adopts five-layer structure, including application layer, transmission layer, network layer, data link layer and physical layer. Seeing Fig. 2 for details.

3.1   Application Layer

According to the requirements of spacecraft data, it can be divided into three types:

1. Low speed, real-time and high reliability data, such as control and telemetry data;
2. High speed, real-time and fluent data, such as image and voice data;
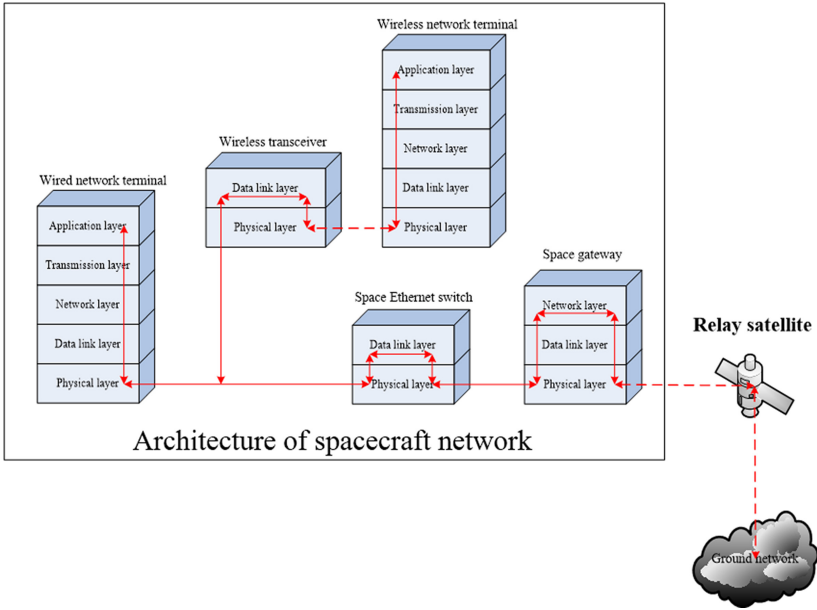3. High speed, reliability, but no real-time requirement data, such as high-speed experiment data.

Fig. 2. Spacecraft network protocol stack

Due to the burst transmission mode of network data, once a variety of data are sent at the same time, it will lead to instantaneous exceeding of the link bandwidth and the loss of data. Therefore, a reasonable control strategy for the network flow must be adopted to avoid network congestion.

According to the characteristics of spacecraft data, three kinds of control strategies for the network flow are adopted, and their corresponding relationships are shown in Table 1.

Table 1. Flow control strategy for spacecraft data

Control strategy	Data
Control strategy 1	Telemetry and control data
Control strategy 2	Image and voice data
Control strategy 3	Experimental data

1. Control strategy 1: for low-speed data with periodicity or randomness and real-time requirements, no flow control is carried out;
2. Control strategy 2: for high-speed data with real-time and fluency requirements, it is required to control the average rate of statistics in a certain period of time. It needs to meet the Eq. (1):

$$V_t \leqslant V_{avg} \tag{1}$$

V_t: the average rate of statistics in t time

V_{avg}: average rate requirement.

3. Control strategy 3: for the high-speed data without real-time requirement, in order to ensure the smooth output data rate of the terminal, the time interval between adjacent data packets is specified, and the output data is required to be buffered and smoothed in the application layer. The time interval of application layer data packets should meet the following Eq. (2):

$$t \geq \frac{L}{v_{avg}} - \frac{L}{v_{max}} \tag{2}$$

t: The time interval between two consecutive frames of data

L: The length of the data in this frame, bits

V_{avg}: average rate requirement

V_{max}: port transmission rate, 100 Mbps.

3.2 Transport Layer

Transport layer adopts connection-oriented transport protocol (TCP) and non-connection-oriented transport protocol (UDP).

TCP Transport Service. TCP adopts acknowledgement mechanism to ensure the reliability of data transmission. Because the format of acknowledgement packet is consistent with that of sending datagram, the overhead of network transmission is increased. The bidirectional delay of the direct to ground link is about 3 ms, and that of the relay satellite link is usually more than 500 ms, which is less than the default TCP retransmission time of 3s. However, due to the imbalance of the bidirectional bandwidth of the transmission link, the downlink bandwidth is usually more than 20 times of the uplink bandwidth, which leads to the low transmission efficiency when using TCP protocol, and the data rate is basically constrained at about 30 kbps. Therefore, for data with high reliability and integrity requirements and low speed (less than 30 kbps), TCP protocol can be used; for data with high speed (more than 30 kbps), TCP protocol is not allowed to be used for data transmission between space and ground. For data with reliability and integrity requirements, it is recommended to adopt corresponding mechanism in application layer to ensure the reliability of data transmission.

UDP Transport Service. UDP protocol adopts connectionless mechanism to ensure the real-time data transmission. Because there is no need to establish a connection, it is not constrained by the imbalance of the bidirectional transmission bandwidth, and it can make full use of the downlink bandwidth to transmit data. Therefore, UDP protocol can be used for data with high real-time requirement and high rate (more than 2 Mbps) to ensure the transmission delay as small as possible.

3.3 Network Layer

Network layer uses IP protocol to realize the data exchange of the network layer. The IP datagram is used to mark the source address, destination address and other information when the network forwards the datagram, so as to realize the routing of the IP datagram.

ICMP Protocol is used in network layer to feedback Internet control messages, which is used to detect and report various errors in IP packet transmission. Terminal equipment and platform equipment select the protocol according to the demand.

ARP protocol is used in network layer to realize the mapping between IP address and physical address. The network of spacecraft only allows ARP broadcast inside the spacecraft, and does not transmit ARP broadcast packets between space and ground.

3.4 Data Link Layer

Data link layer of spacecraft network mainly includes Ethernet data link layer, wireless WIFI data link layer and space-ground transmission data link layer.

Ethernet Data Link Layer. The data link layer of wired network terminal adopts the MAC frame format of IEEE Std 802.3TM-2005, and does not use LLC sublayer. In order to avoid the MAC address conflict of the spacecraft network terminal equipment, the terminal developer needs to purchase the commercial network card and configure the spacecraft terminal MAC address as the commercial network card MAC address. Make sure that the MAC address is not used by other terminals.

Wireless WIFI Data Link Layer. The wireless terminal is connected to the Ethernet of spacecraft through the wireless transceiver device, which can communicate with other Ethernet terminals of spacecraft and the ground in two directions. The wireless transceiver device adopts the two-layer forwarding data mode, stores the MAC forwarding table internally, extracts the data link layer information of the incoming data, forwards the data according to the destination MAC address, and compares the source MAC address with the destination MAC address. The corresponding relation of the port is updated to the MAC forwarding table. The wired network interface of wireless transceiver meets the 10Base-T/100base-TX standard of IEEE 802.3 and 802.3u specifications, and the radio frequency interface meets the IEEE 802.11g/n transmission specification.

Data Link Layer of Space Ground Transmission. The data link layer adopts IP over CCSDS protocol. The gateway device encapsulates the Ethernet MAC frame in the AOS frame data area through CCSDS package protocol, which realizes the conversion between the Ethernet transmission protocol and the ground link transmission protocol. Due to the mismatch between the length of data frame (generally defined as 1024 bytes) and the length of MAC frame (generally defined as 1500 bytes), invalid data will be filled at the end of data frame of the link if the IP packet is directly divided according to the length of MAC frame for encapsulation. It will result in the waste of link bandwidth. In order to solve this problem, this paper proposes a network packet segmentation strategy based on the data frame format of the link. The IP packet length is divided into MAC frames according to the link data frame length, which ensures that

the IP packet length is consistent with the link data frame length, and avoids invalid filling packets in the link. It can greatly improve the utilization of the link. Compared with 74% in MAC frame length division, the utilization is increased to 86% and the improvement is more than 10%.

3.5 Physical Layer

The network terminals of spacecraft are distributed inside and outside the cabin. The vacuum environment outside the cabin is alternating high and low temperature, and inside the cabin is the constant temperature environment. The network signal transmission inside and outside the cabin must use the through cabin connector.

There is signal crosstalk problem in the transmission of 100 MHz Ethernet signal by through cabin connector [10]. In order to solve this problem, by analyzing the electric field distribution of the connector, a low electromagnetic interference arrangement method of cross arrangement and cable group shielding is proposed for the multi-channel high-density connector, which optimizes the electric field distribution between the wires in the connector, reduces the mutual influence of the transceiver line, and improves the performance of the near end. The crosstalk is optimized by 8dB, which solves the problem of crosstalk between high-speed transmission lines and multi-channel high-density connectors, and realizes the stable transmission of 100 MHz Ethernet signal for network terminals inside and outside the cabin in the space environment.

4 Network Communication Mode

4.1 Autonomous Addressing Mechanism for Spacecraft Network

ARP protocol can be used to establish and maintain the corresponding relationship between MAC address and IP address in the internal network terminal of spacecraft. The space switch maintains the storage table of the switch through the corresponding relationship between MAC address and port of the received data. When the switch receives a frame of data packet, it looks up whether there is a storage item of the destination MAC address in the storage table. If there is no such item, it will send a broadcast frame to all terminals. When the other party feeds back the data information, it can store and update the relationship between the MAC address and the port.

The table stored in the switch and terminal is provided with the latest update time information. The data exchanged by the terminal and the switch is required to maintain and update the storage table. When the update is not carried out for a long time, the corresponding items in the table should be deleted to prevent the normal communication of the network affected by the network topology and terminal status changes. ARP query is performed again before the ARP cache table of terminal is aged, and the storage content is updated with feedback information. The autonomous addressing mechanism of spacecraft network is shown in Fig. 3:
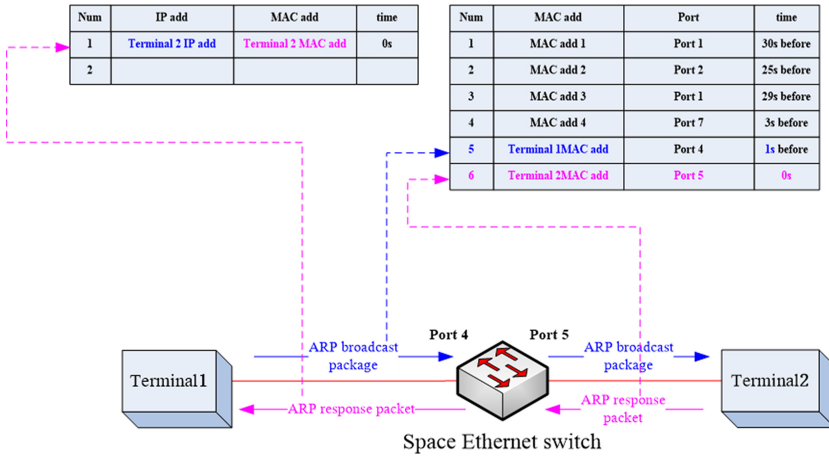
Num	IP add	MAC add	time
1	Terminal 2 IP add	Terminal 2 MAC add	0s
2			

Num	MAC add	Port	time
1	MAC add 1	Port 1	30s before
2	MAC add 2	Port 2	25s before
3	MAC add 3	Port 1	29s before
4	MAC add 4	Port 7	3s before
5	Terminal 1MAC add	Port 4	1s before
6	Terminal 2MAC add	Port 5	0s

Fig. 3. Autonomous addressing mechanism for spacecraft network

4.2 Dynamic Routing Mechanism in Space-Ground Network

Three-layer data forwarding mode is adopted between the spacecraft and the ground network. The communication mode between the spacecraft network terminal and the ground network terminal is different from that of the internal network of the spacecraft. The protocol processing function of the space-ground link needs to be completed by the space-ground gateway.

When the spacecraft network terminal needs to send the data to the ground terminal, the network terminal judges whether the destination IP address is an internal address before transmitting the data. If it is an internal address, layer 2 exchange is carried out directly. If it is an external address, the default gateway MAC address is queried through ARP protocol, and the IP packet is sent to the gateway through the switch. After receiving the packet, the gateway encapsulates the IP packet and transmits it to the ground through CCSDS AOS protocol. When the ground receives the data, it forwards the IP packet to the corresponding ground network terminal. The data processing process of up-link is consistent with that of down-link. Seeing Fig. 4 for the dynamic routing mechanism of the space-ground network.

5 Experiment

In order to verify the design of the spacecraft network architecture and protocol stack proposed in this paper, the experiment is carried out through the space-ground test. The network equipment of spacecraft, space-ground link and ground station network are all real equipments. In the test, the transmission delay test, image and voice transmission test are carried out.

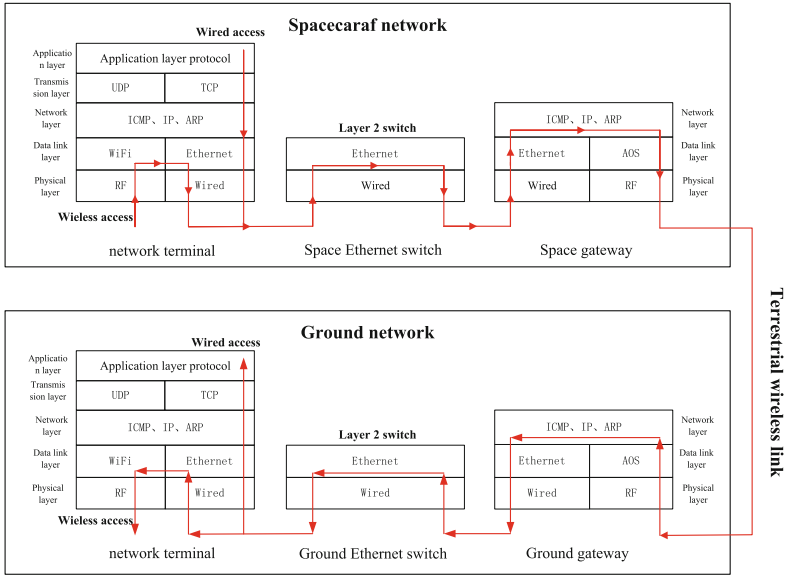The transmission delay of space-ground IP packets is about 526 ms, as shown in Fig. 5.

Fig. 4. Dynamic routing mechanism in space-ground network

Fig. 5. Transmission delay test

The HD image down-link is normal, and the image is clear and smooth, as shown in Fig. 6.

The voice transmission is normal, the voice rate is controlled evenly with an average of 60 packets per second (see Fig. 7 for details), the voice is smooth, and there is no packet loss.

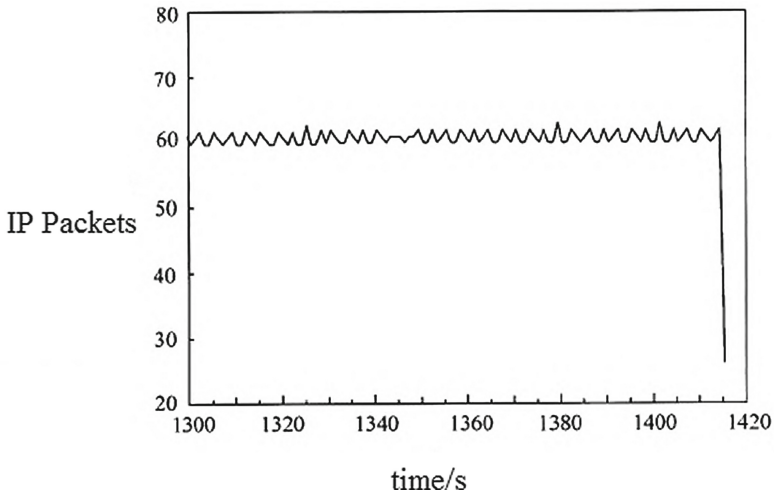**Fig. 6.** Image transmission test

Fig. 7. Voice transmission test

6   Conclusion

In this paper, a network architecture and protocol stack for spacecraft are proposed and verified, which can realize efficient and reliable space-ground integrated network communication.

The spacecraft network system can be applied to the space-ground integrated network of high, medium and low earth orbit spacecraft represented by manned spacecraft, and can also be applied to deep space exploration missions. At the same time, it provides a technical way for commercial network products to access the spacecraft network, promotes the on-orbit application of commercial products, and has great social benefits and application prospects.

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