RESEARCH OF PROTOCOL STACKS FOR FUTURE SPACE NETWORKS

Huang Wei[1] Wan Peng[1] Song Shijie[1] Liu Feng[2]

1 Beijing Institute of Tracking and Telecommunication Technology
2 School of Electronics and Information Engineering, Beihang University

ABSTRACT

The increasing of space explorations requires space communication protocols to provide more capabilities, such as dynamic routing, adaptive data transformation and automatic resource allocation. Accordingly, a universal space communication protocol stack should be provided instead of specially designing protocol for given space mission. Considering the requirements and characters of space mission, potential protocols of all layers were compared and analyzed. Simulations were made based on OPNET. And a suggestion for space communication protocol stacks is proposed.

KEY WORDS

Space network, CCSDS, IP, Protocol stacks

INTRODUCTION

The increasing of space explorations requires space communication protocols to provide more capabilities, such as dynamic routing, adaptive data transformation and automatic resource allocation. Standardization is also need to increase cross-support between different space agencies and decrease development costs. As the practical international standard organization in space communication area, CCSDS has proposed a protocol stack, which layered from data link layer to application layer. And more than 400 international space missions have adopted CCSDS protocols. At the same time, constructing an IP-based space network is also an attractive solution. So what protocol stack that future space network should base on is an attractive research issue.

The future space network consists of two parts, the space link and the ground link. Since it has been recognized that TCP/IP should be adopted in the ground link, the focus of our research is the space link. The scenarios considered are missions that are up to lunar distance. And the traffics considered are telecommand, telemetry, and payload data.

This paper is organized as follows. In section 2, according to the requirements and characters of space mission, potential protocols of all layers were compared and analyzed, and issues that need simulations were also list. In section 3, the realization of simulation was described briefly. In section 4, the results of experiment were presented and analyzed. We concluded in section 5.

ANALYSIS OF POTENTIAL PROTOCOL STACKS

Data Link Layer Protocol CCSDS has presented a set of space data link protocols, including telemetry space data link protocol, telecommand space data link protocol, AOS space data link protocol, and Proximity-1 space data link protocol. Since specially designed for space mission, supported by many space agencies, and has been researched and partially supported in China, CCSDS protocols are selected as data link layer protocols. And the optimized lengths of packet and transfer frame will be found by simulation.

Network Layer Protocol CCSDS has presented two network layer protocols, which are space packet protocol and SCPS-NP. IP is also an attractive option. The three protocols are analyzed and compared in several aspects, such as protocol functions, address space, overhead, the technical maturity, and COTS support. And the main protocol functions considered include the ability of supporting managed connections, the ability of supporting mobility, the ability of selecting routing mode by protocol mechanism, the way to maintenance routing table ,the ability of processing packet based on its priority, the ability of controlling the life time of packet, the ability of providing signaling mechanism to aid upper layer process and network management, the ability of segmentation of upper layer PDU, and the interconnection with IP-based ground network.

Fully relying on management mechanism to establish end-to-end connections, space packet protocol provides the simplest functions with the least overhead. But it isn't suitable for a space network with dynamic paths.

The contents of SCPS-NP header can be configured according to the provided functions. Thus the overhead may be reduced. But SCPS-NP has almost the same overhead with space packet or IP if it provides the same function as them.

IP can support almost all of the functions provided by space packet protocol or SCPS-NP. There have been solutions for IP mobility management. And IP-based space network can interconnect directly with IP-based ground network. Compared with CCSDS network protocol, IP is more technically mature, and has more COTS support. So technically, IP is an ideal selection for space network layer protocol. There have been header compression mechanisms to reduce IP header overhead. The adaptability of such mechanisms to space communications environment should be evaluated by simulation.

TRANSPORT AND APPLICATION LAYER PROTOCOL The transport and application layer protocols are configured in end systems, and will not influence the intermediate nodes and interconnections of different networks. The application layer protocols should be selected according to the requirements and characteristics of traffics. The transport layer protocols should cover the possible gaps between the requirements of application layer and services provided by network layer.

The traffics considered are telecommand, blind command, telemetry, and payload data. As to telemetry and blind command, the performance of end-to-end delay is primary concerned. So UDP is selected for these two traffics, which mainly provides ports. The custom-built application software will be developed to process telemetry information or provide commanding strategy to meet an emergency. For all space missions, there is requirement of providing some degree of end-to-end reliability for telecommand and payload traffic. So some upper layer protocol mechanism should be selected to meet above reliability requirement.

End-to-end reliability can be realized in transport layer or application layer. CFDP and MDP are file protocols which provide reliability in application layer. SCPS-TP and TCP are stream protocols which provide reliability in transport layer. Since telecommand traffic is suitable to be treated as stream, SCPS-TP or TCP can be selected. Payload traffic can be treated either as stream or file, SCPS-TP, TCP, CFDP or MDP can be considered. The final selection lies on the performance of above protocols in space communication environment, which needs simulation. CCSDS telecommand space data link protocol provides point-to-point reliability in data link layer by COP-1 option. The compare and interaction between COP-1 and end-to-end reliability mechanism also need evaluating by simulation.

THE REALIZATION OF SIMULATION

Considering the propagating delay, the traffic type and traffic load, four simulation scenarios were designed. Scenario one corresponds to LEO mission supported by ground station. Scenario two corresponds to LEO mission supported by TDRSS. Scenario three corresponds to lunar mission. And scenario four corresponds to GEO mission. Telemetry, telecommand and payload traffics are supported by the first three scenarios. The last scenario only supports telemetry and telecommand traffic. Several parameters can be configured, such as bit error rate, the data rates of forward and return link, the traffic type, and so on.

Simulations are made based on OPNET. A set of OPNET process models have been developed to realize CCSDS TC, AOS, SCPS-TP ,CFDP and MDP. Node models have been built to simulate mission center, ground stations and spacecrafts. And several simulations have been run under different scenarios and configurations.

SIMULATION RESULTS AND ANALYSIS

EXPERIMENT ONE: PARAMETERS OPTIMIZATION OF CCSDS SPACE DATA LINK PROTOCOLS The purpose of this experiment is to find the optimal packet length of CCSDS TC protocol, and the optimal combination of packet length and transfer frame length of CCSDS AOS protocol. The criterion is throughput. As to CCSDS TC and AOS protocol, the throughput is mainly influenced by bit rate, the method of constructing frame, and overhead, and has little relationship with delay and transmitting rate. So this experiment is run under only one scenario and one data rate. The result is showed in Table 1.

Table 1 THE OPTIMAL PARAMETERS OF CCSDS SPACE DATA LINK PROTOCOLS

BER	CCSDS TC PROTOCOL		CCSDS AOS PROTOCOL	
	OPL[1] (Bytes)	OI[2] (Bytes)	OPL/OFL[3] (Bytes)	OI[2] (Bytes)
10^{-5}	512	[512，1024]	1000/512	PL[4]：[512，1024] FL[5]：[128，1024]
10^{-6}	2048	[512，30000]	4000/2048	PL[4]：[512，10000] FL[5]：[512，2048]
10^{-7}	65000	[1024，65000]	30000/512	PL[4]：[512，4096] FL[5]：[512，2048]

NOTE:
1 Optimal Packet Length.
2 Optimal Interval. When packet length or frame length falls in the optimal interval, the difference between achieved throughput and optimal throughput is within 10%.
3 Optimal Frame Length.
4 Packet Length.
5 Frame Length.

As showed in Table 1, the throughput varies slowly near the optimal configures. And there are overlaps among the optimal intervals under different bit error rate. In the following experiments, the packet length of CCSDS TC is set as 1024 Bytes. With that packet length, the difference between achieved throughput and optimal throughput is within 5.5%. The packet length of CCSDS AOS is set as 1000 Bytes, and the frame length is set as 512 Bytes. With that combination, the difference between achieved throughput and optimal throughput is within 3%.

EXPERIMENT TWO: PERFORMANCE EVALUATION FOR TELECOMMAND TRAFFIC

The purpose of this experiment is to compare the performance of telecommand traffic supported by different protocol configures, such as TCP, SCPS-TP, TCP plus COP-1, SCPS-TP plus COP-1, and UDP plus COP-1. The criterion is throughput rate and end-to-end delay. The main simulation parameters are showed in Table 2.

Table 2 THE MAIN SIMULATION PARAMETERS OF EXPERIMENT TWO

Simulation scenarios			Scenario1	Scenario2	Scenario3	Scenario4
The Altitude of Orbit（km）			1100	500, 36000	400000	36000
Data Rate	Forward（kbps）		2	2	1	2
	Return（kbps）		5	5	1	5
BER			10^{-5},10^{-6},10^{-7}			
Lower Protocol Configures	Network Layer		IPv4			
	Data Link Layer	Forward	CCSDS TC			
		Return	CCSDS AOS			
Packet Length	Forward (Bytes)		16～1024			
	Return (Bytes)		1000			
Frame Length	Forward (Bytes)		Matching with packet length			
	Return (Bytes)		512			

Since the forward data rate is rather low, transmission delay will dominate in end-to-end delay. The traffic model in application layer will have great influence in simulation result. Considering the characteristic of actual telecommand traffic, a traffic model is designed to evaluate the protocol configures' adaptability to varied packet lengths and burst traffic. The length of packet produced by application layer obeys even distribution between 16 Bytes and 1024 Bytes, and will be selected equiprobably every 30 seconds. During simulation, application layer will not produce packet in two time intervals and will transmit packet by double rates in another two time intervals. So the traffic produced by application layer has some degree of burst, but its average rate will not excess the capability of lower link during the whole simulation. The simulation results of throughput rate and end-to-end delay are showed respectively in Table 3 and Table 4.

Table 3 THE THROUGHPUT RATE IN EXPERIMENT TWO

BER	Simulation scenarios	Protocol Configures				
		TCP	SCPS-TP	UDP+COP-1	TCP+COP-1	SCPS-TP+COP-1
10^{-5}	Scenario 1	54.9%	56.9%	48.1%	51.0%	55.8%
	Scenario 2	54.1%	56.1%	48.1%	49.2%	54.0%
	Scenario 3	47.8%	49.8%	30.4%	46.1%	49.2%
	Scenario 4	54.1%	56.1%	48.1%	49.2%	54.0%
10^{-6}	Scenario 1	56.9%	56.9%	55.5%	56.1%	56.1%
	Scenario 2	56.9%	56.9%	55.5%	56.1%	56.1%
	Scenario 3	49.8%	49.8%	48.0%	49.8%	49.8%
	Scenario 4	56.9%	56.9%	55.5%	56.1%	56.1%

10^{-7}	Scenario 1	56.9%	56.9%	55.5%	56.1%	56.1%
	Scenario 2	56.9%	56.9%	55.5%	56.1%	56.1%
	Scenario 3	49.8%	49.8%	48.0%	49.8%	49.8%
	Scenario 4	56.9%	56.9%	55.5%	56.1%	56.1%

Table 3 THE END-TO-END DELAY IN EXPERIMENT TWO

BER	Simulation scenarios	Protocol Configures				
		TCP	SCPS-TP	UDP+COP-1	TCP+COP-1	SCPS-TP+COP-1
10^{-5}	Scenario 1	8.2 s	3.0 s	11.2 s	4.8 s	5.1 s
	Scenario 2	8.9 s	4.1 s	11.8 s	5.4 s	5.7 s
	Scenario 3	14.3 s	10.9 s	45.9 s	10.8	11.3 s
	Scenario 4	8.5 s	3.7 s	11.5 s	5.1 s	5.4 s
10^{-6}	Scenario 1	2.4 s	2.3 s	2.0 s	2.1 s	2.4 s
	Scenario 2	3.3 s	3.1 s	2.6 s	2.7 s	3.0 s
	Scenario 3	7.6 s	7.6 s	7.0 s	8.8 s	7.6 s
	Scenario 4	2.9 s	2.8 s	2.3 s	2.4 s	2.7 s
10^{-7}	Scenario 1	2.0 s	2.0 s	1.9 s	2.0 s	2.1 s
	Scenario 2	2.6 s	2.6 s	2.5 s	2.6 s	2.7 s
	Scenario 3	7.6 s	7.6 s	7.0 s	8.8 s	7.6 s
	Scenario 4	2.3 s	2.3 s	2.2 s	2.3 s	2.4 s

When BER is 10^{-6} and 10^{-7}, the throughput rate of all protocol configures approaches. The differences are within 2%. When BER is 10^{-5}, there is more notable difference among the throughput rates of different protocol configures. The throughput rate of SCPS-TP is best in either BER.

When BER is 10^{-6} and 10^{-7}, the end-to-end delay of all protocol configures approaches. The differences are within 2 second. When BER is 10^{-5}, there is more notable difference among the delay of different protocol configures. The delay of SCPS-TP is least in either BER.

From the simulation result, the following conclusions can be derived:

- The BER requirement of telecommand traffic is usually 10^{-5}, and may be upgraded to 10^{-7}. SCPS-TP works best in such BER interval. So it’s the best candidate protocol for telecommand.
- Without cooperation, applying reliability mechanism concurrently in data link layer and transport layer can’t further improve performance. Since SCPS-TP has been selected, it isn’t recommended to enable COP-1 concurrently.
- Since traffic model of application layer has in-depth effect on delay and throughput performance, the length of packet produced by application layer should be designed carefully in mission engineering.

EXPERIMENT THREE: PERFORMANCE EVALUATION FOR PAYLOAD TRAFFIC

The purpose of this experiment is to compare the performance of payload traffic supported by different protocol configures, such as TCP, SCPS-TP, CFDP, and MDP. The main simulation parameters are showed in Table 5. Payload traffic is transferred as files. The criterion is throughput rate, the average file transfer time, and the percent of successfully received files. The sender will produce and transmit files by a rate matching the physical channel rate. The size of single file is set as 1M Bytes.

Table 5 THE MAIN SIMULATION PARAMETERS OF EXPERIMENT THREE

<table>
<tr><td colspan="3">Simulation scenarios</td><td>Scenario1</td><td>Scenario2</td><td>Scenario3</td></tr>
<tr><td colspan="3">The Altitude of Orbit（km）</td><td>1100</td><td>500, 36000</td><td>400000</td></tr>
<tr><td rowspan="2">Data Rate</td><td colspan="2">Forward（kbps）</td><td>2</td><td>2</td><td>1</td></tr>
<tr><td colspan="2">Return（Mbps）</td><td>10</td><td>10</td><td>1</td></tr>
<tr><td colspan="3">BER</td><td colspan="3">10^{-7}</td></tr>
<tr><td rowspan="4">Protocol Configures</td><td colspan="2">Transport and Application Layer</td><td colspan="3">SCPS-TP, CFDP+UDP, MDP+UDP, TCP</td></tr>
<tr><td colspan="2">Network Layer</td><td colspan="3">IPv4</td></tr>
<tr><td rowspan="2">Data Link Layer</td><td>Forward</td><td colspan="3">CCSDS TC</td></tr>
<tr><td>Return</td><td colspan="3">CCSDS AOS</td></tr>
<tr><td rowspan="2">Packet Length</td><td colspan="2">Forward (Bytes)</td><td colspan="3">16～1024</td></tr>
<tr><td colspan="2">Return (Bytes)</td><td colspan="3">1000</td></tr>
<tr><td rowspan="2">Frame Length</td><td colspan="2">Forward (Bytes)</td><td colspan="3">Matching with packet length</td></tr>
<tr><td colspan="2">Return (Bytes)</td><td colspan="3">512</td></tr>
</table>

SCPS-TP and TCP can’t work because the ratio of return and forward data rate is about 5000:1, largely excess the threshold of SCPS-TP and TCP. The performance of CFDP and MDP approaches when BER is 10^{-7}. The throughput rate can achieve about 80%. The percent of successfully received file can achieve near 100% in scenario3. In other scenarios, the percent of successfully received file is under 50%. File is divided into small fragments. If under the constraint of retransmission times, there still exits fragment that hasn’t been successfully received, the file that this fragment belong to will not be treated as a successfully received file. But other fragments of this file that have been successfully received will be adopted when calculating throughput rate. So there is difference between the percent of successfully received files and throughput rate. Smaller file size or higher feedback channel rate should be selected to improve the percent of successfully received files.

With further simulations, it’s found that when file size is under 128k Bytes, the percent of successfully received files can upgrade to 90%. To achieve 100%, the feedback channel rate should be raised. When the payload traffic transmission rate is 10Mbit/s, the feedback channel rate should be upgrade to 50kbps. Considering the traffic requirement on that channel is usually about 2kbps, this method is too costly.

It’s difficult to realize 100% successfully payload file transfer with reliability. It is recommended to reasonably set the file size and only provide reliability service for key data instead of for all data.

EXPERIMENT FOUR: EVALUATION OF HEADER COMPRESSION MECHANISM The performance of UDP/IP header compression mechanism is evaluated by comparing the packet loss rate with and without header compression. The performance of SCPS-TP/IP header compression mechanism is evaluated by comparing the throughput and delay with and without header compression. The simulation result is showed in Table 6 and Table 7. From the result, introducing header compression doesn't have obvious negative effect.

Table 6 SIMULATION RESULTS OF SCPS-TP/IP HEADER COMPRESSION

BER	Protocol Configures					
	Without Header Compression			With Header Compression		
	Number of packets received by transport layer	Number of Packets submitted by transport layer	End-to end delay (s)	Number of packets received by transport layer	Number of Packets submitted by transport layer	End-to end delay (s)
10^{-5}	787808	718520	2.23	801939	716087	2.27
10^{-6}	780416	718520	1.87	782734	718520	1.86
10^{-7}	775232	722616	1.72	777372	724946	1.70

Table 7 SIMULATION RESULTS OF UDP/IP HEADER COMPRESSION

BER	Protocol Configures			
	Without Header Compression		With Header Compression	
	Packet Loss Rate with 1024 Bytes Packet Length	Packet Loss Rate with 16Bytes Packet Length	Packet Loss Rate with 1024 Bytes Packet Length	Packet Loss Rate with 16Bytes Packet Length
10^{-5}	12.5%	0.36%	10.2%	0.18%
10^{-6}	1.4%	0.04%	1.2%	0.022%
10^{-7}	0.04%	0.01%	0.02%	0.01%

EXPERIMENT FIVE: EVALUATION OF PROTOCOL EFFICIENCY The purpose of this experiment is to compare the efficiency of compressed UDP/IP, compressed SCPS-TP/IP and CCSDS Space Packet protocol. The simulation result is showed in Table 8. With header compression and appropriate configure, the efficiency of SCPS-TP and UDP approaches Space Packet Protocol.

Table 8 SIMULATION RESULTS OF PROTOCOL EFFICIENCY

Traffic Type	Protocol Configures (Transport Layer/Network Layer/Data Link Layer)		Protocol Efficiency
Telecommand	SCPS-TP [1]/IP/TC		96.65%
	UDP/IP/TC	TC without aggregation [2]	84.05%
		TC with aggregation [3]	94.35%

<table>
<tr><td rowspan="2"></td><td rowspan="2">SP/TC</td><td>TC without aggregation [2]</td><td>86.71%</td></tr>
<tr><td>TC with aggregation [3]</td><td>94.35%</td></tr>
<tr><td rowspan="4">Telemetry or Payload Data</td><td rowspan="2">UDP/IP/AOS</td><td>With Packet Length of 16 Bytes</td><td>77.74%</td></tr>
<tr><td>With Packet Length of 1024 Bytes</td><td>97.21%</td></tr>
<tr><td rowspan="2">SP/AOS</td><td>With Packet Length of 16 Bytes</td><td>71.03%</td></tr>
<tr><td>With Packet Length of 1024 Bytes</td><td>97.07%</td></tr>
<tr><td colspan="4">NOTE
1：Nagle Option is enabled. And the length of segment is set as 1000Bytes.
2：Every packet received from network layer constructs an individual frame.
3：Several packets received from network layer can be aggregated in the same frame so long as the frame length isn’t excess 1024Bytes.</td></tr>
</table>

CONCLUSIONS From the results of simulations, the following conclusions can be derived:

- SCPS-TP is recommended for telecommand traffic.
- CFDP is recommended for payload traffic.
- Since IP can provide more integrated functions and its overhead can be reduced greatly by header compression mechanism, IP is recommended as network layer protocol.
- Traffic model of application layer has in-depth effect on performance. To meet the QoS requirement of specific traffic, the length of packet produced by application layer or the size of file should be carefully designed.

SUGGESTION OF PROTOCOL STACKS FOR FUTURE SPACE NETWORKS

IP-BASED PROTOCOL STACK Based on the conclusion of simulation, the following protocol stack is recommended:

- Data Link Layer: CCSDS AOS or TC
- Network Layer: IP
- Transport Layer and Application Layer:
  - Telemetry: UDP
  - Blind Command: UDP
  - Telecommand :SCPS-TP
  - Payload Data: CFDP

CCSDS PROTOCOL STACK Although IP is technically advanced, applying IP in space requires more complicated on-board processing. For rather long time, many space missions don’t have strong requirements for IP’s versatility. It would be very difficult to convince such missions to adopt IP. At the same time, reliability and timeliness is more preferred than flexibility and extensibility in channels that provide basic telecommand and telemetry service in urgent condition. So CCSDS protocol stacks will still be needed. The CCSDS protocol stacks is as following:

- Data Link Layer: CCSDS AOS or TC
- Network Layer: CCSDS Space Packet
- Application Layer :CFDP

Telemetry and telecommand are supported by space packet protocol. The reliability of telecommand can realize by COP-1 or other self-defined strategy realized in application layer. The payload data can be treated as bitstream directly supported by AOS or packets. If payload data need some kinds of reliability, it can be realized by CFDP.

INTERNETWORKING Since IP-based protocol stack and CCSDS protocol stack will coexist, CCSDS SLE or other self-defined interface protocol that acts similarly as SLE will be adopted in ground stations and centers to realize space traffics exchanging on ground.

CONCLUSION

In this paper, protocols of all layers that may be applied in space communication are analyzed and evaluated by simulations. And a suggestion of protocol stacks for future space networks is presented. Actually, protocol is only one of factors influencing QoS. When multiple types of traffics and multiple upper layer protocols coexist, how to meet the QoS requirements of different traffics by reasonable resources management is an open research issue.

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