Research and Analysis of Flow Control Mechanism for Transport Protocols of the SpaceWire Onboard Networks

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Introduction

Flow control plays an important role for onboard systems of the space vehicles. Each node of the onboard network should have valid information on the status of other network devices.

The flow control mechanism helps to synchronize the data transmission rate of the transmitting and receiving sides, i.e. to give ability to transmit the data to the receiving side in accordance with the free buffer space in the receiver.

We developed the STP-ISS protocol (rev. 2) for onboard networks and we got the requirement:

- *STP- ISS should have possibility to transfer the large-sized packets via the specific transport connection.*

So we got a task to implement a connection-oriented data transmission with the flow control mechanism to avoid the data loss during the transmission.

For this purpose we analyzed the flow control mechanisms of the following protocols:

- well-known existing industrial protocols (Infiniband, Fibre Channel, PCI Express, USB 3.1),
- protocols for mobile communications (UniPro),
- protocols for global networks (TCP/IP)
- onboard networks (SpaceWire, GigaSpaceWire, SpaceFibre, JRDDP, STP).

Infiniband

InfiniBand *is high performance architecture designed for exchange of the data between the servers, communication systems and storage devices at high speed (up to 25.8 Gbps).*

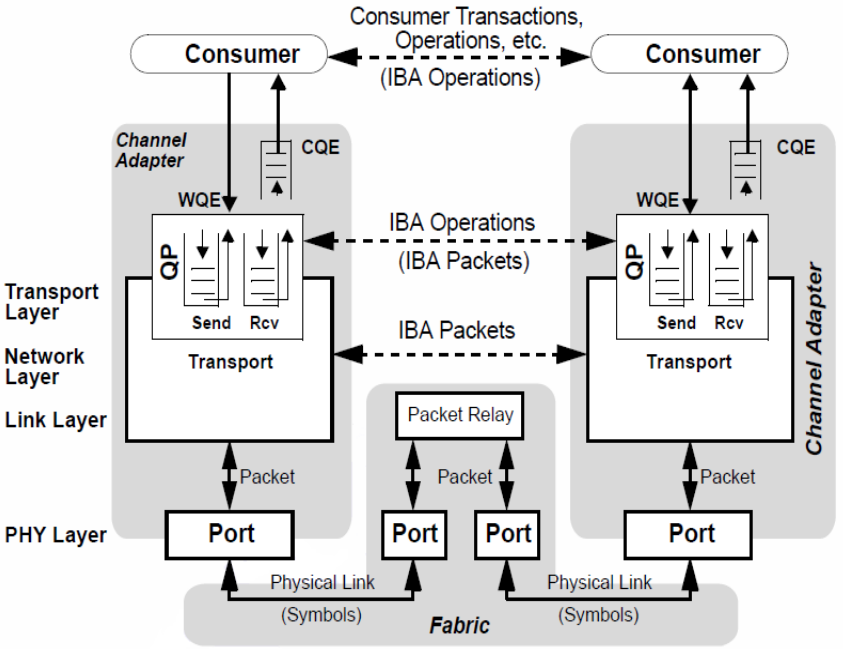


Fig.1. Infiniband protocol stack

Flow control at the data link layer

- It is sending of the number of credits in special ***flow control packets*** through Virtual link;
- Each packet contains a field with the receiver's credit limit.
- Transmitter sends an FC packet with the number of packets to transmit.
- Receiver gets FC packet, stores the number of packets value, and sends the response control packet with the credit limit field.
- Transmitter is able to send data packets if:

$$[(Received\_credit\_limit - transmitted\_packets\_number)\ \mathbf{MOD}\ 4096] < 2048.$$

End-to-end flow control at the transport layer

- the transmitter requests available credits from the receiver;
- receiver generates credits, encodes it and sends to the transmitter as a confirmation message;
- the available credits are stored in a special field of the message header.

PCI Express

PCI Express *is a computer bus, which is represented by a set of consecutive channels with the point-to-point connection on a physical layer. PCI Express uses a software model of PCI bus and high-performance protocol based on serial transmission of data.*

PCI Express uses the *credit-based flow control* mechanism at the network layer (PCI Express transaction layer).

- *FC could be used after a virtual channel establishment.*

- FC information is transmitted by means of the FC packets, which contain receiver's free buffer space information;
- Transmitter stores the number of receiver's credits in a *available credits counter*. When a packet successfully transmitted – available credits counter value is reduced.
- If the available credits value is less than the size of a transmitting packet, the transmission should be stopped until the transmitter will receive the new credits information.
- When receiver gets the packet it releases the receiving buffer, updates the available buffer space information and transmits new flow control packet to the transmitter.

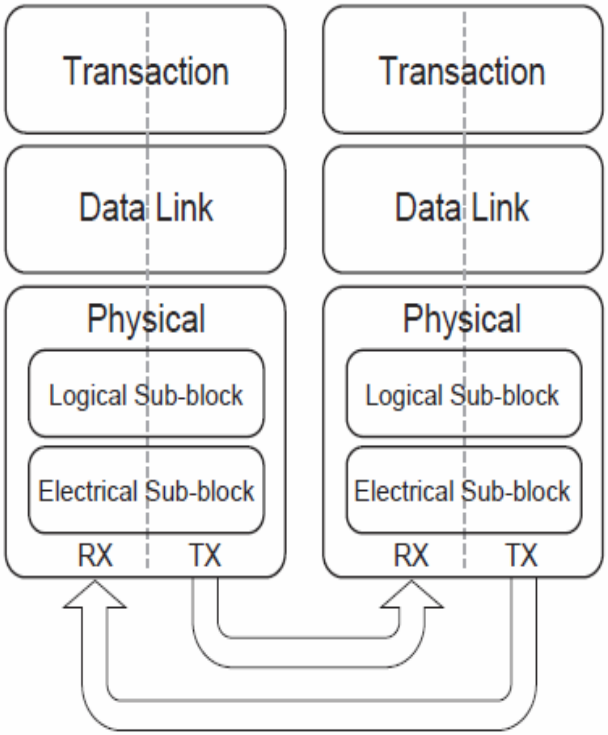


Fig.2. PCI Express protocol stack

USB 3.1

USB *(Universal Serial Bus) is a serial data transmission interface for medium-speed and low-speed devices. The main advantage of USB 3.1 is the data transmission speed up to 10 GB/s.*

End-to-end flow control at the network layer (USB 3.1 Protocol Layer).

FC mechanism uses special transaction packets: *ACK, NRDY (NOT READY), ERDY (ENDPOINT READY).*

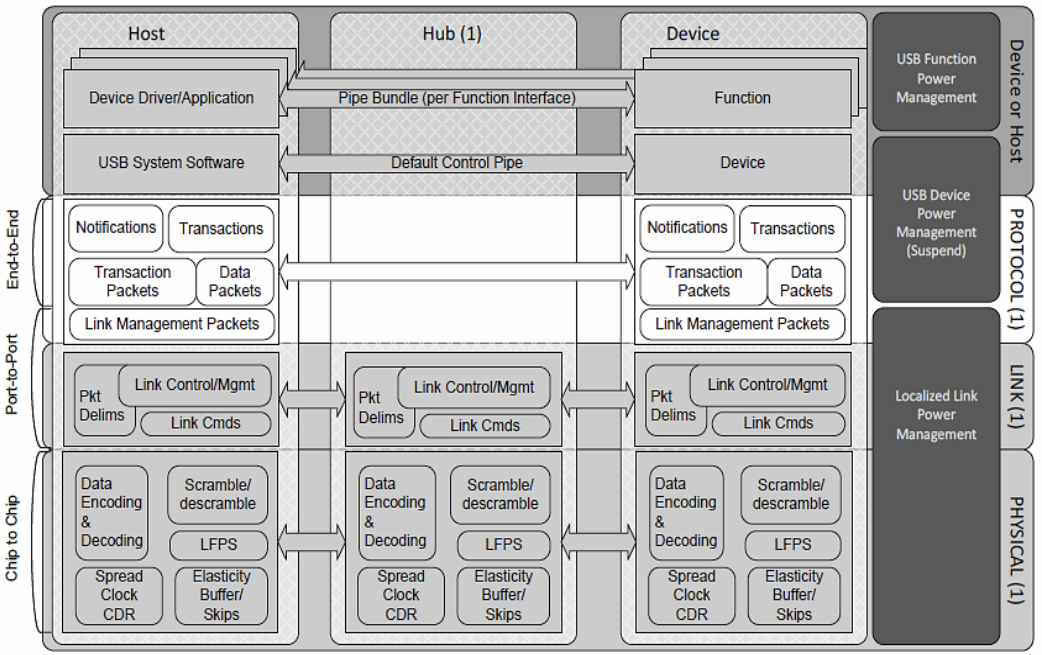


Fig.3. USB 3.1 protocol stack

- Before the data exchange starts, host sends to the device an ACK packet with sequence indicator SEQ and a number of packets NumP to identify the data transmission flow.
- If the NumP differs, the host re-sends the ACK with the required NumP, so the device re-sends the packets.
- The last packet of the sequence is marked with a special flag. After that if the device sends the ERDY packet, the host responds with an ACK and transmission is continued.
- If the host expects the data transmission from the device, and the device is not ready, it sends NRDY packet.

Fibre Channel

Fibre Channel *is a protocol stack for implementation of Storage Area Networks (SAN), which provide high-speed data transfer.*

Flow control in Fibre Channel Protocol is implemented in two mechanisms: “buffer-to-buffer” and “end-to-end” management.

Buffer-to-buffer FC is used for the data exchange between two ports.

- All the frames incoming to the input port should be stored in special buffers. 1 buffer = 1 credit.
- Each port has *transmitted credits counter* and *received credits counter*.
- In the sending port credits counter value should be decremented after the sending of each frame.
- Transmission stops if counter value equals to zero.
- When receiving port gets an ACK, the value of the transmitted credits counter shall be incremented by 1.
- When the receiving port got the data, the frame is stored to the RX buffer, received credits counter is decremented.
- If the frame is transmitted from the buffer – the received credits counter is incremented and an Ack is sent.

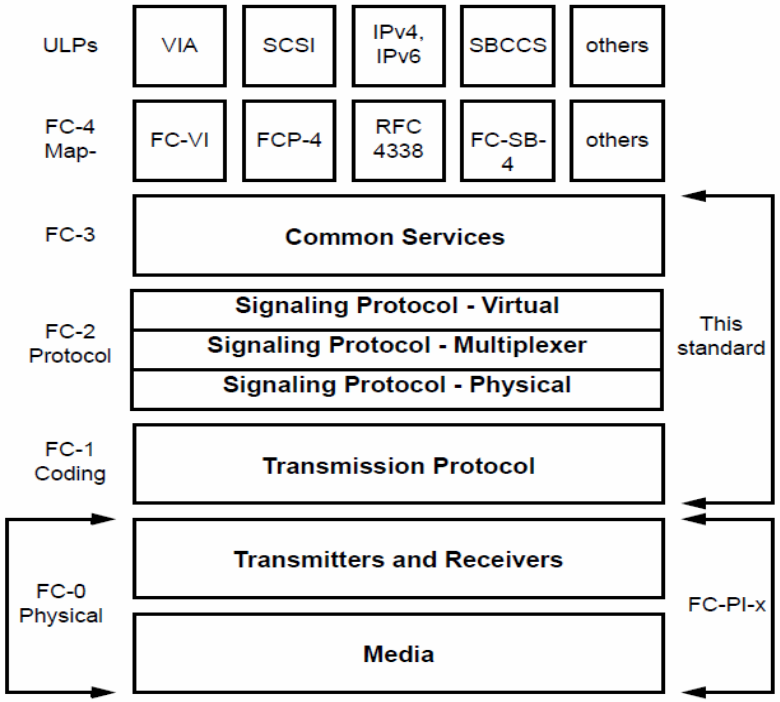


Fig.4. Fibre Channel Structure

End-to-end FC mechanism is used for the data exchange between the end nodes.

- Each node has received credits counter and transmitted credits counter. These counters are applied to the data frames.
- The transmitted credits counter counts the maximum number of frames that the transmitter can send without receiving of an acknowledgement.
- The received credits counter counts the number of credits that the receiver can receive without sending an acknowledgement.

TCP/IP

TCP/IP *is an industrial protocol stack designed for global networks.*

TCP protocol defines the flow control mechanism called ***"sliding window"****, which allows the sender to send the next segment without waiting for the confirmation from the destination point of the preceding segment.*

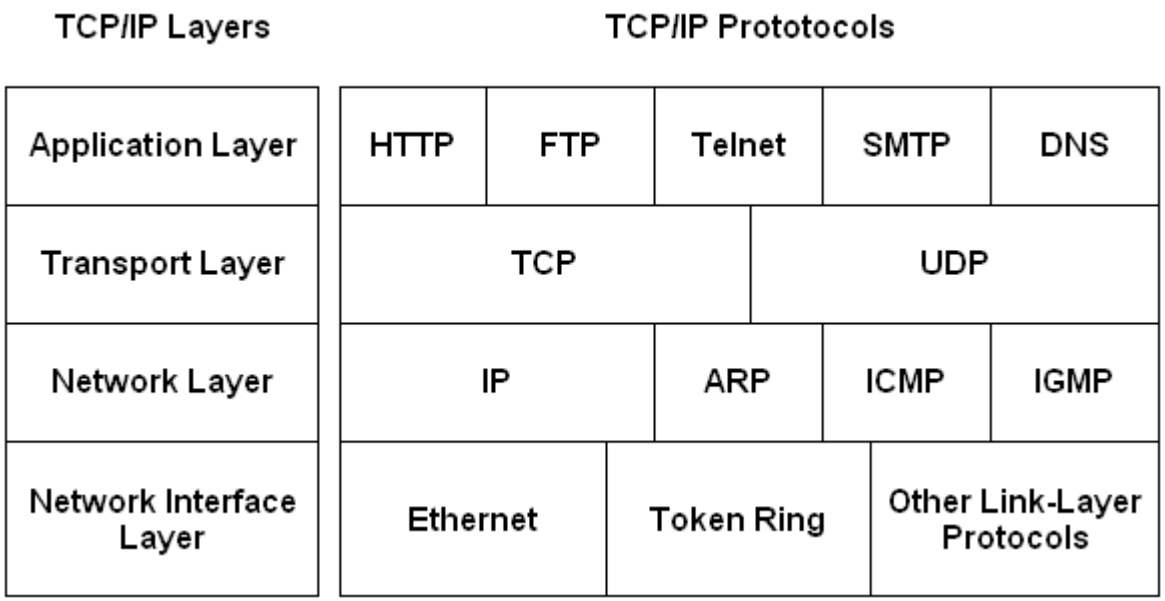


Fig.5. TCP/IP Protocol Stack

- TCP generates acknowledgments for all data from the beginning of the transmission and till the some serial number ACK SN (Acknowledge Sequence Number).
- To confirm the successful reception of the first N bytes receiver sends ACK SN = N+1, which acknowledges receipt of the data from (ACK SN-N+1) till the (ACK SN-1).
- After that receiver declares the sliding window size to get the next transmitting data: the sender can send data with sequence numbers from the current *ACK SN* till the *ACK SN+window size-1* (without waiting for ACK).
- The receiver can dynamically change the window size.
- The size of the window is selected such a way that the acknowledgment has to be successfully transmitted and transmission does not stop.

UniPro *(or Unified Protocol) is a high-speed interface technology for interconnecting integrated circuits in mobile and mobile-influenced electronics such as mobile phones, laptops, digital cameras and multimedia devices.*

Credit-based flow control is used on the **Data Link layer**. The receiver transmits available credits information via special frames:

- AFC (acknowledgment and flow control) and NAC frames (negative acknowledgement) with no application data.
- Transmitter sends the data frames – receiver sends the AFC responses with available buffer space in the receiver .
- UniPro supports the multiple data frames confirmation by one AFC frame.
- NAC frames are sent if receiving frames are corrupted.

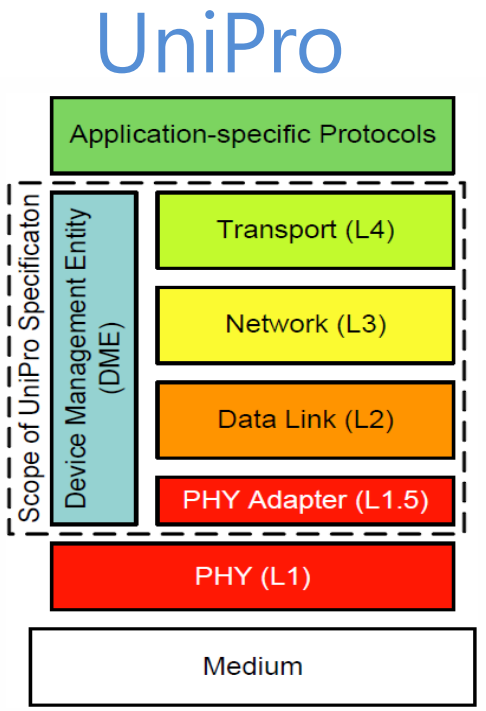


Fig.6. UniPro Protocol Stack

At the **transport layer** UniPro protocol uses **end-to-end flow control**.

It is performed by sending of receiver free buffer space information.

- During the connection establishment both sides define the transmission direction and the value of the control token in bytes.
- Receiver has an available credits counter. Transmitter has a free buffer space counter.
- After the connection establishment receiver starts to send messages with a control token until the available credits counter value will not be less than the control token value .
- The transmitter receives messages with tokens, the counter increments the available buffer space by a control token value.
- Once the size of the available buffer space counter is greater or equal to the size of the message to be sent, then the transmitter sends the message.
- After that, the number of transmitted bytes is subtracted from the available buffer space counter value.

SpaceWire

SpaceWire *standard is intended for data transmission and information management of onboard equipment for aircraft and spacecraft. This standard uses a high-speed (2 - 400 Mbit / s) full-duplex links that meet high reliability requirements, independence from receiving and transmitting hardware and other aerospace requirements.*

SpaceWire controls the data flow by ***credit based flow control***.

- ❑ The transmitter is able to send symbols only if the receiving buffer has free space for them.
- ❑ Receiver informs that it has free buffer space for 8 information characters by sending an FCT - Flow Control Token.
- ❑ This symbol gives an ability for transmitter to send eight information characters.
- ❑ If the receive buffer in a host-system allows to take more than eight information symbols, the transmitter may send multiple flow control symbols.

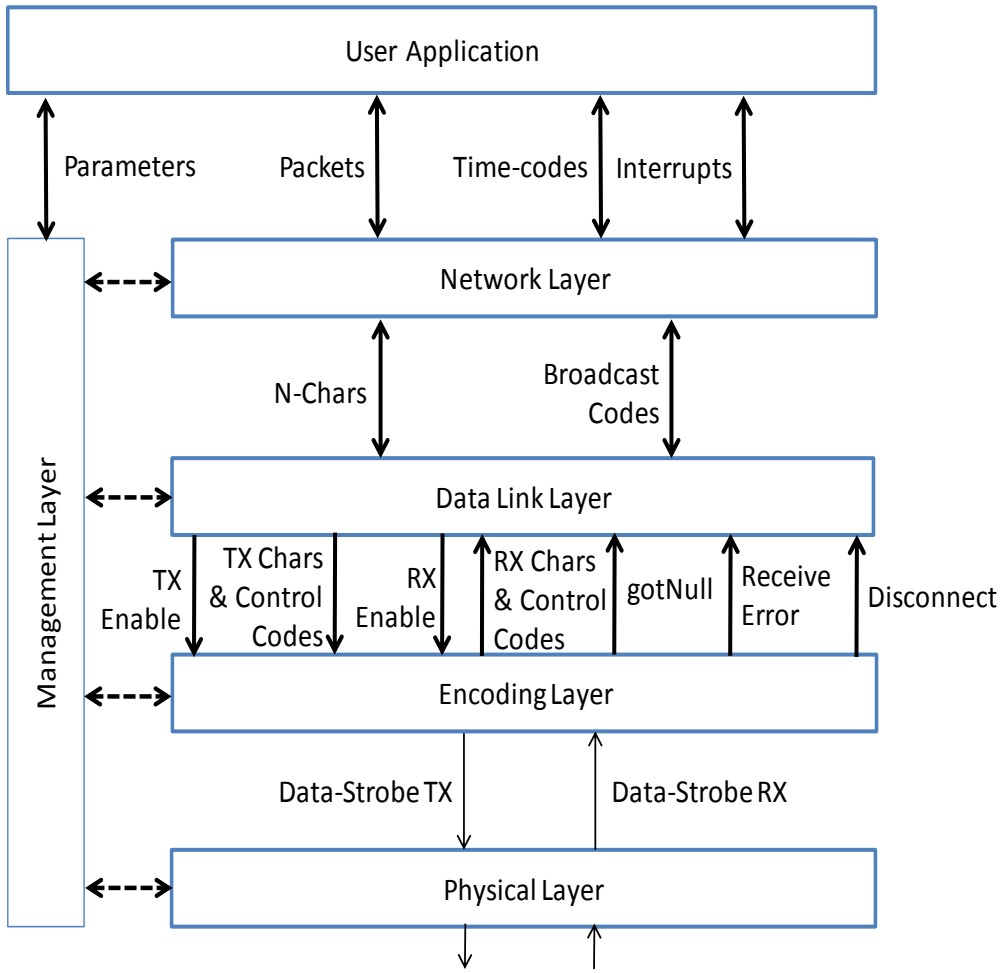


Fig.7. SpaceWire Protocol Stack

GigaSpaceWire

GigaSpaceWire *protocol stack uses network and packet layers of SpaceWire and introduces new exchange, character, coding and PHY layers.*

GigaSpaceWire flow control mechanism can operate in SpaceWire flow control mode and in GigaSpaceWire flow control mode.

The main difference between GigaSpaceWire flow control mode and SpaceWire flow control mode is in the number of information bits, which carry a flow control character FCT.

- SpaceWire mode one FCT corresponds to 8 N-Chars
- GigaSpaceWire mode one FCT corresponds to 32 characters.

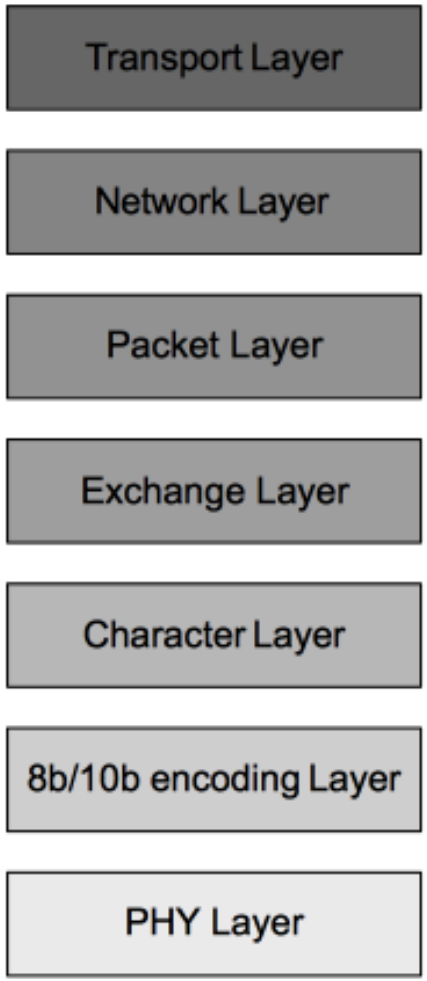


Fig.9. GigaSpaceWire Protocol Stack

SpaceFibre

SpaceFibre *is a spacecraft standard that allows to transfer data via fiber optic and copper cables and supports data rates up to 2 Gbit/s and 20 Gbit/s. SpaceFibre provides a mechanism to ensure the quality of service that can support guaranteed delivery, priority, guaranteed bandwidth and scheduling quality of service.*

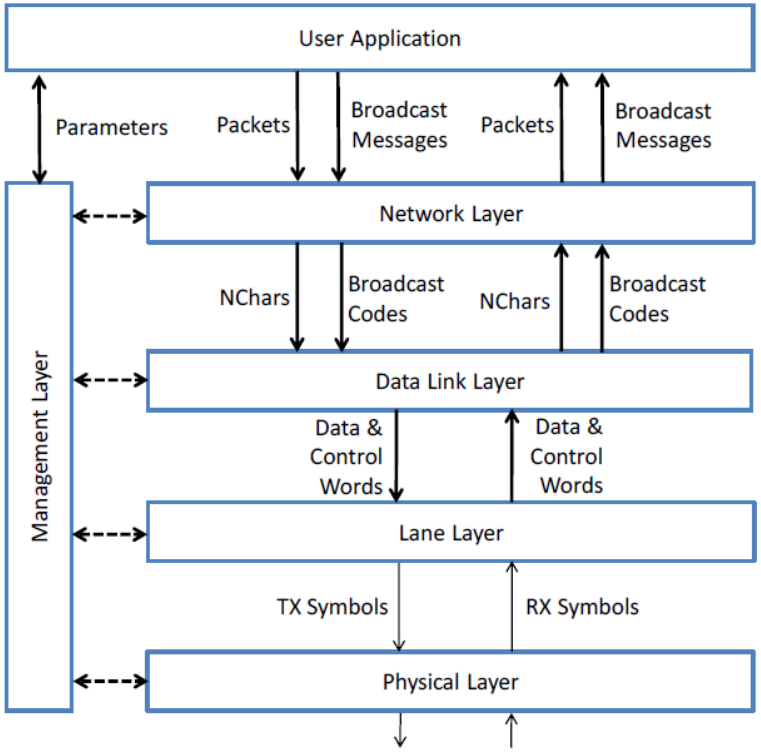


Fig.8. SpaceFibre Protocol Stack

SpaceFibre link layer ***uses credit-based flow control*** mechanism for virtual channels.

- ❑ The transmitter can send frames only if the receiving buffer at the remote side of the channel has free space.
- ❑ The receiver indicates that it has free space for more than 256 N-Char characters by FCTs.
- ❑ The transmitter has to keep track of all received FCT symbols.
- ❑ When a certain virtual channel received FCT, FCT credit counter should be incremented by 256.
- ❑ When a particular virtual channel sends a data frame, the value of FCT credit counter should be decremented by the number of N-Char characters and FILLs, that was send in this frame.
- ❑ If a data frame is ready for transmission, the size of the frame is compared with the FCT counter value .
- ❑ If FCT credit counter >= data frame size, frame transmission starts.
- ❑ If the FCT credit counter value overflows, FCT should be discarded, counter should be set to its maximum value.

JRDDP

JRDDP *is a transport protocol for reliable data delivery for SpaceWire networks. It provides reliable services of data delivery to a multiple applications using the SpaceWire.*

JRDDP uses ***"sliding window" flow control*** at the **transport layer**.

- ❑The size of the sliding window is defined during transport connection establishment (256 max).
- ❑The receive window range shall start with the next data packet sequence number and end with start sequence number plus window size minus 1.
- ❑When receiver gets the next packet - the receive window shall be incremented by 1.
- ❑Size of the window could be extended, if the receiver gets two or more packets with adjacent sequence number
- ❑Each successfully received and processed packet is confirmed by ACK packet.
- ❑If a received packet has sequence number out of the window, it shall be discarded.
- ❑A duplicate packet which has a sequence number inside the window should be acknowledged, but discarded.
- ❑The transmitter has its own transmit window, which size equals to sliding window.
- ❑The beginning of transmit window shall be incremented by 1 when the ACK for the first sequence number is received.

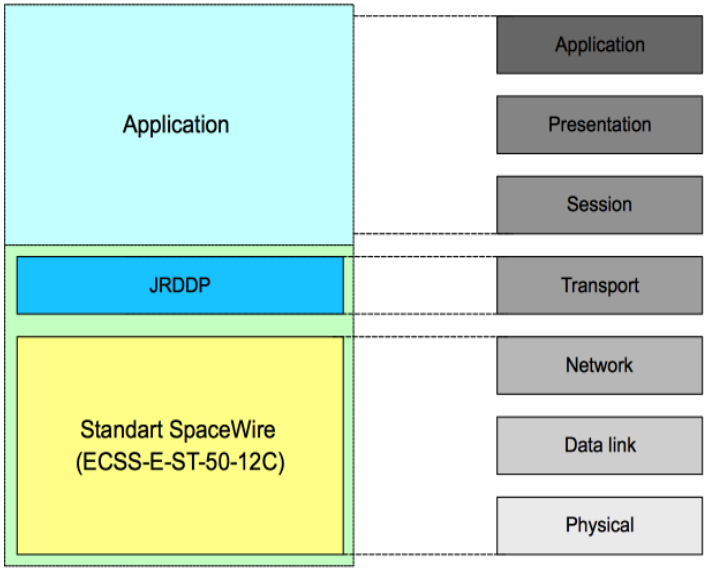


Fig.10. JRDDP Protocol Stack

SpaceWire-R

SpaceWire-R *is a protocol that provides onboard applications with reliable data transfer services over SpaceWire networks.*

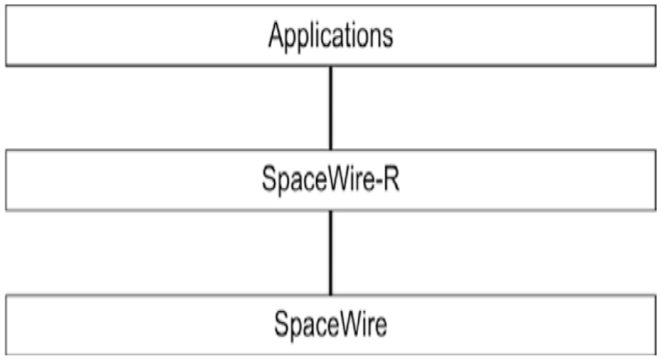


Fig.11. SpaceWire-R Protocol Stack

Flow control in SpaceWire-R Protocol is implemented in two mechanisms: ***"sliding window"*** **and** ***"modified sliding window"*****.**

- The ***sliding window*** shall be a range of k consecutive Sequence Numbers.
- The size of the sliding window shall be less or equal to 128.
- When the receiver gets the acknowledgement, sliding window range should be incremented by 1.
- The first Data Packet shall have Sequence Number 1.
- If the Sequence Number of next packet is not in the range of sliding window, transmission shall be stopped until it would not be included to the sliding window.

If ***modified sliding window flow control*** is used, the data transmission shall be modified as follows:

- When the previously transmitted Data Packet had Sequence Number *m*, the next Data Packet to be transmitted shall have Sequence Number *m*+1.
- If *m*+1 is less than or equal to the Maximum Acceptable Sequence Number (MASN = 256), it shall be transmitted immediately.
- If not, its transmission shall be stopped until *m*+1 becomes less than or equal to the MASN.

STP

STP *is transport protocol is designed for the simultaneous transmission of multiple streaming data flows in SpaceWire networks.*

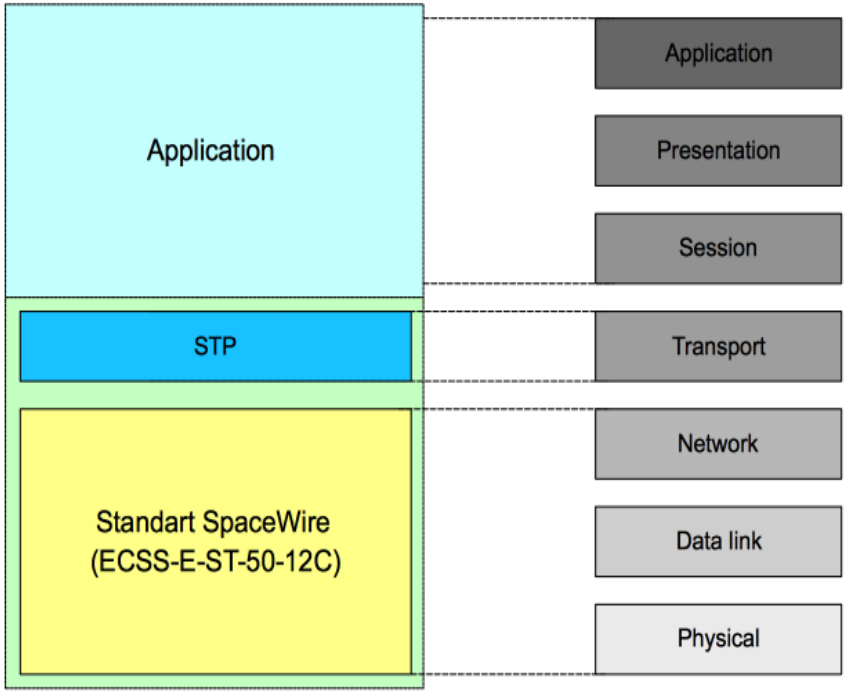


Fig.12. STP Protocol Stack

STP also uses ***end-to-end flow control*** mechanism.

- During the connection establishment, receiver gives credits to N packets, which could be received.
- If the receiver sends N = 0, that means that transmitter has an unlimited number of packets.
- When the connection is established, the receiver sends a command to start the transfer of data packets.
- Transmitter sends the number of packets equal to the number of received credits.
- If the transmitter is allowed to transfer N packets, it should stop the transmission and wait for new credits from the receiver.

RapidIO

RapidIO *is a high-performance packet-switched, interconnect technology. RapidIO can be used as a chip-to-chip, board-to-board, and chassis-to-chassis interconnect.*

The Physical layer of the RapidIO protocol uses ***credit- based flow control*** mechanism. This mechanism has two operating modes: **receiver-controlled** and **transmitter-controlled** flow control.

In Receiver-controlled flow control, the input side of a port controls the flow of packets from its link partner by accepting or rejecting (retrying) packets on a packet by packet basis.

- ❑ The receiving port does not provide information on amount of buffer space.
- ❑ Transmitter sends packets with no expectations whether a given packet will be accepted or rejected.

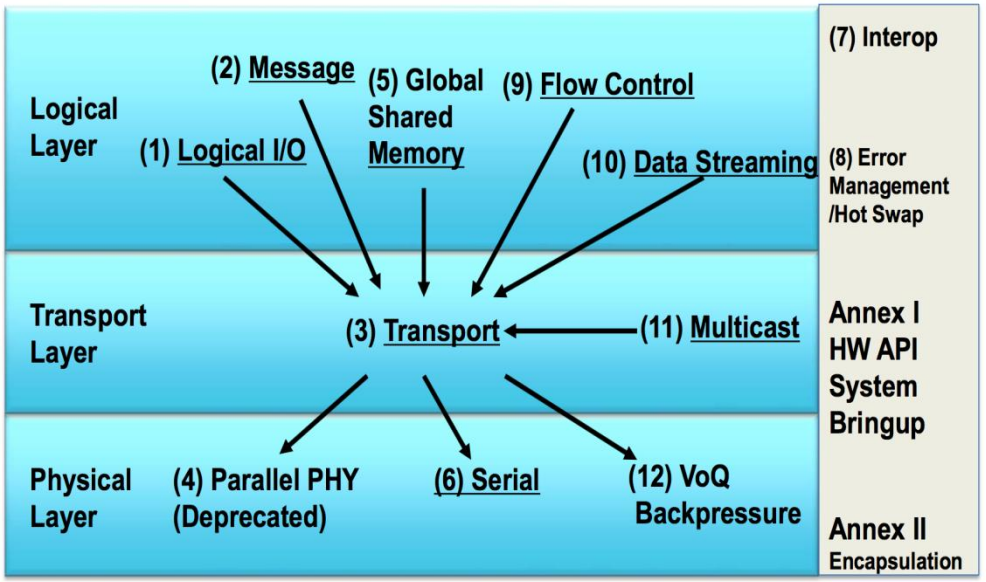


Fig.13. RapidIO Protocol Structure

In transmitter-controlled flow control, the receiving port provides this information to transmitter – so the sending port can work with receiving buffers according to the number and priority of packets can retry some transmissions.

At the RapidIO Logical layer protocol uses ***end-to-end flow control***, which is performed by sending FLOW_CONTROL messages between nodes.

There are three types of flow control behavior which can be specified:

1. use the XON command to enable data traffic.
2. use the XOFF command to suspend data traffic.
3. In the case that data traffic is suspended, RTS message can be used to inform the stream owner (data receiver) that data is available to be sent.

COMPARISON OF THE CONSIDERED PROTOCOLS (1/2)

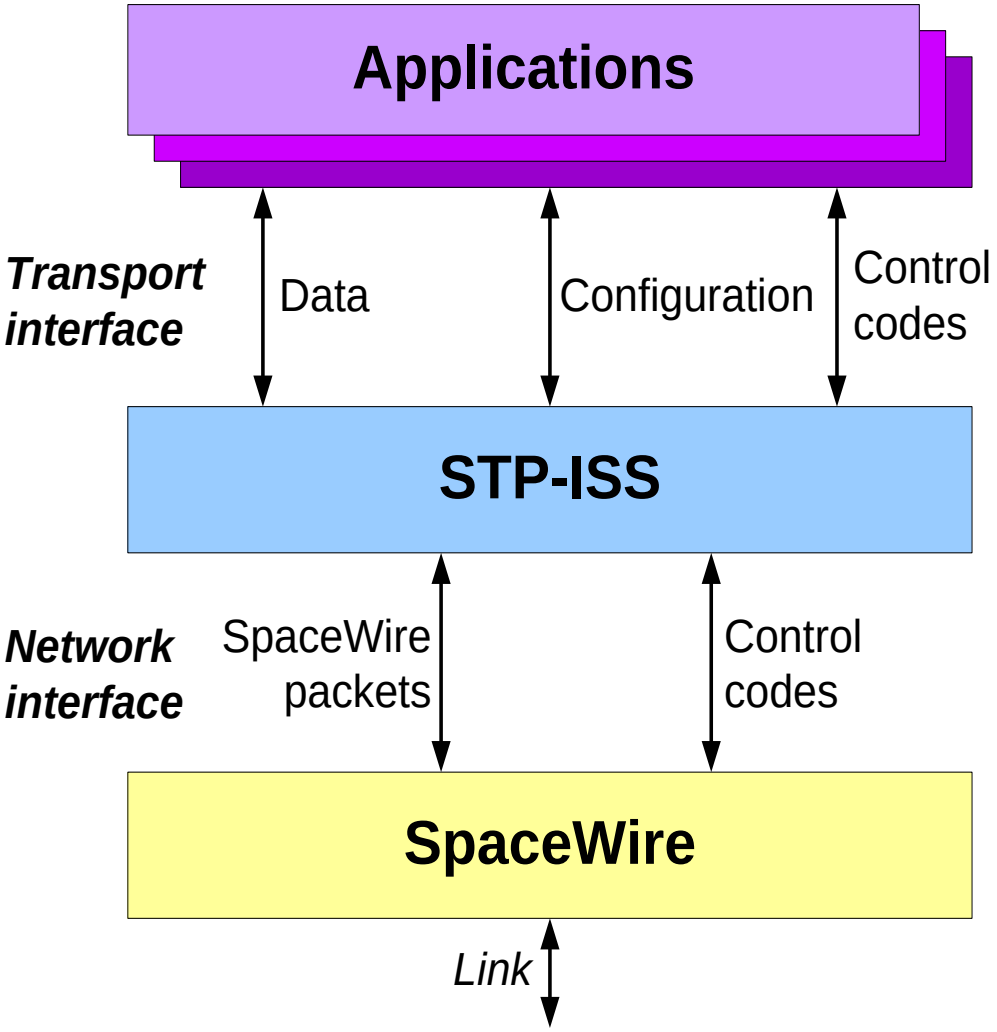
- We compare the protocols by different parameters: application of the protocols, flow control types, characteristics of flow control, the layer of application, etc.
- Flow control mechanisms can be divided into two main groups:
  - ❑ flow control with feedback (the receiver allows the transmitter to continue data transmission or report the receiver status);
  - ❑ limited flow control (the protocol limits the transmitter's rate, no acknowledgements from the receiver)

- All the overviewed protocols use the scheme with feedback, and all flow control mechanisms (from the link layer to the transport layer) based on the credit exchange mechanism, as the most effective one. This mechanism has the following main features:
  - ❑ buffering at the transmitting and the receiving side;
  - ❑ credits are equal to bytes of data;
  - ❑ credit information is updated by acknowledgments.

COMPARISON OF THE CONSIDERED PROTOCOLS (2/2)

Parameters \ Protocols	Infiniband	Fibre Channel	PCI Express	USB 3.1	TCP/IP	UniPro	SpaceWire	SpaceFibre	GigaSpaceWire	JRDDP	SpaceWire-R	RapidIO	STP
Scope Of Application	HPCN, CC	HPS, SAN	HPS, HSTDSI	PR	LAN, WAN	MSD	OE	OE	OE	SN	SN	OE	SN
Layers OSI	CL, TL	NL	NL	CNL	TL	CL, TL	CL	CL	CL	TL	TL	CL, NL	TL
Credit-Based FC	√	-	√	-	-	√	√	√	√	-	√	√	-
End-To-End FC	√	√	-	√	-	-	-	-	-	-	-	√	√
Buffer-To-Buffer FC	-	√	-	-	-	-	-	-	-	-	-	-	-
Sliding Window FC	-	-	-	-	√	-	-	-	-	√	√	-	-
Support Connection	√	√	√	√	√	√	-	√	-	√	√	√	√
Unit Credit	1 byte	1 data frame	16 byte	packet id	1 packet	1 byte	8 char symbols	256 char symbols	8 or 32 char symbols	packet id	packet id	1 packet	packet id
Max Data Size In Bytes	4096	2048	4096	1025	64K	306	no limit	256	no limit	64K	no limit	64K	4G

STP-ISS



- A transport protocol developed under the grant agreement between SUAI and JSC "ISS"
- STP-ISS works on top of SpaceWire
- Two STP-ISS revisions
- Three types of user messages:
  - Common Messages
  - Urgent Messages
  - Control Commands

STP-ISS Revisions

STP-ISS revision 1

- Priority QoS
- Guaranteed QoS
- Best effort QoS
- Connectionless data transmission
- CRC check
- Reset & Flush
- Packet lifetime timer
- Protocol configuration possibility
- Maximum data length 2 Kb

STP-ISS revision 2 (additionally to rev. 1)

- Scheduling QoS
- Connection-oriented data transmission
- Flow Control
- Duplicate control commands detection
- Maximum data length 64 Kb for connection-oriented packets

- Backward compatibility is provided

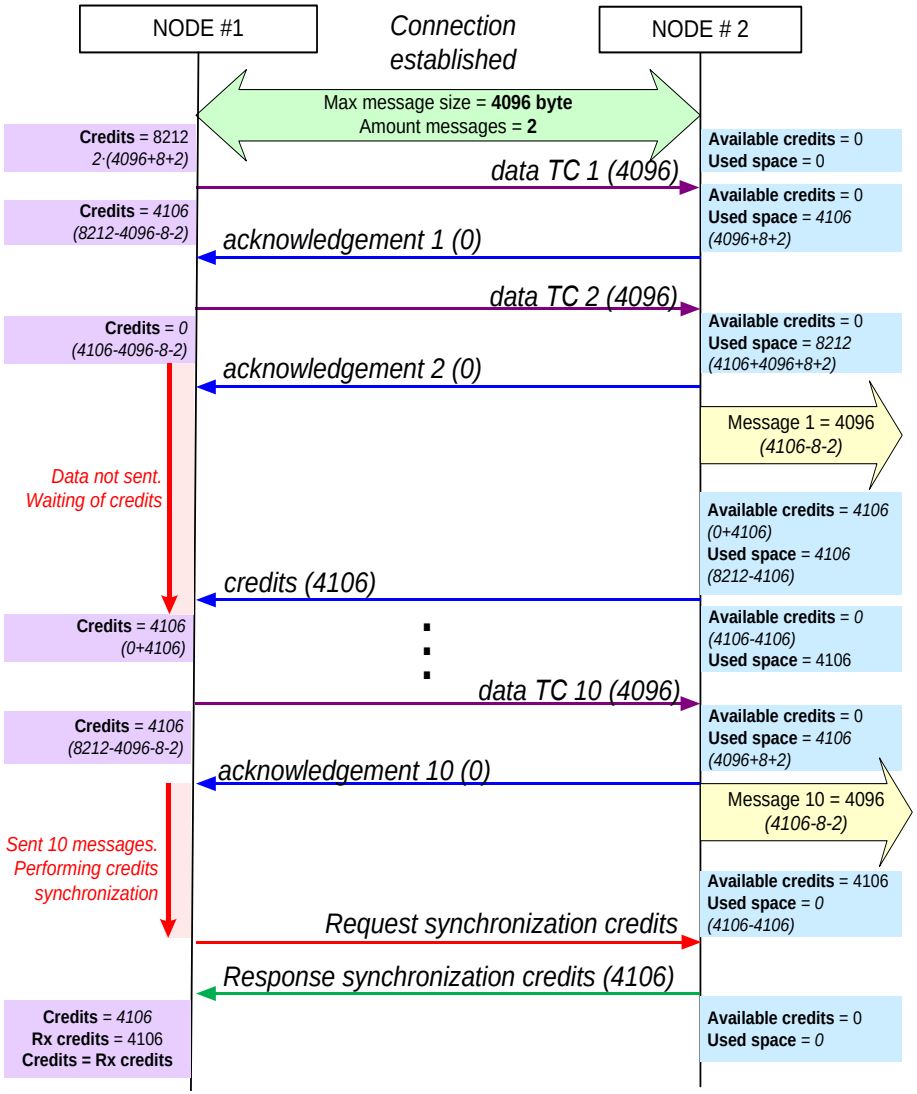
DEVELOPED FLOW CONTROL MECHANISM FOR STP-ISS (1/2)

The receiving buffer size in STP-ISS could be very small (only for two packets) and it is necessary to count the number of transferred bytes, which could not be done by using of the "sliding window" mechanism. Therefore, we use **end-to-end flow control** mechanism.

- Using STP-ISS flow control mechanism receiver should send the information on the amount of free space in the receive buffer (for STP-ISS transport connections with Guaranteed quality of service).
- During the connection establishment the receiver should reserve the buffer space and count it with a *free credits counter* and *used buffer space counter*.
- Information on buffer free space should be sent in acknowledgements.
- If the value of free space in the buffer changes, then the receiver sends an acknowledgment packet with a special flag that tells that it is not an acknowledgment packet, but just credits.
- The transmitting node gets the new information and updates the internal counter.
- To avoid loss of credits information (in case of corruption of acknowledgement packet) STP-ISS uses *credits synchronization mechanism*.

DEVELOPED FLOW CONTROL MECHANISM FOR STP-ISS (2/2)

- Synchronization of credits between the receiver and a transmitter should be carried out after each N (currently – 10) packets are sent to the receiver.
- For these purpose transmitting node send the credit synchronization request. Receiver gets this packet and responds with the current value of credits counter.
- Then the transmitter checks if his credits number value is still valid.



CONCLUSION

1. We analyzed the flow control mechanisms of different protocols:
   - well-known existing industrial protocols (Infiniband, Fibre Channel, PCI Express, USB 3.1),
   - protocols for mobile communications (UniPro),
   - protocols for global networks (TCP/IP)
   - onboard networks (SpaceWire, GigaSpaceWire, SpaceFibre, JRDDP, STP).

2. We compared them and defined what is needed for STP-ISS protocol.

3. We developed the Flow Control mechanism for STP-ISS connection-oriented data transmission mode.

Thank you!