SpaceFibre Virtual Channels Behavior under Control Stimuli

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***Abstract*—When developing on-board equipment for SpaceFibre spacecraft networks, the task of analyzing the Virtual Channels operating states of SpaceFibre switch is important, because SpaceFibre switch is significant for spacecraft operations, because it directly transmits scientific, functional and command data. Analysis of the Virtual Channels operating states of SpaceFibre switch allows to determine how switch will work under various control stimuli. The analysis is performed using mathematical modeling based on the theory of finite state machine and computer modeling. It is significant to keep spacecraft operational.**

I. Introduction

When developing onboard communication equipment for SpaceFibre spacecraft networks [1], the task of analyzing the operating states of SpaceFibre switch is important, because SpaceFibre switch directly transfers scientific, functional and command data to spacecraft systems. The task of diagnosing the fails of SpaceFibre switch is important to keep spacecraft operational. Switch is responsible for communications between onboard systems: it directly transmits scientific, functional and command data to spacecraft systems. Analysis of the operating states of SpaceFibre switch allows to determine how switch will work under various control stimuli.

A. *SpaceFibre Virtual Channels*

SpaceFibre (SpFi) is a standard for high-speed data transmission (channel speeds of 1.25, 2.5 Gbit/s and in the future up to 20 Gbit/s), that created for use in onboard space equipment [2].

Data Link Layer with only Virtual Channels and only Medium Access Control (MAC) of SpaceFibre standard is considered in the paper. The SpaceFibre switch has input and output ports. Each input/output port consists of virtual channels (VC). Every VC has buffers for sending and receiving data.

Packets with data arrive in the output port and are stored in one of VCs into sending buffer (Fig. 1). Data can be sent if the following conditions are met: 1) sending buffer has data with length of at least 256 N-Char (hereinafter – byte) or EOP/EEP was recorded into buffer; 2) there is a free buffer space for at least 256 bytes into receiving buffer of remote input port, because FCT was received previously; 3) if VC has the highest Precedence and VC is scheduled to be sent in the current time-slot ("Scheduling" QoS), then VC will be allowed to send data; 4) link is not busy by sending previous data.

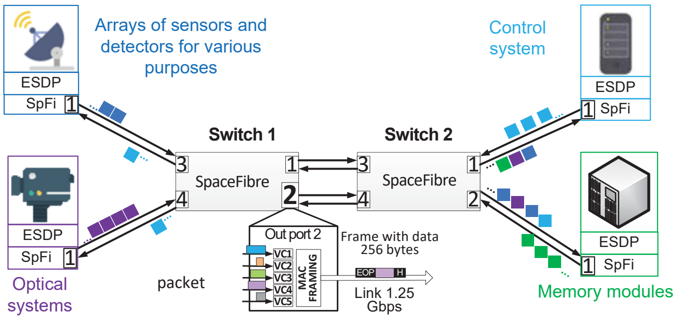

Fig. 1. An example of a SpaceFibre network with virtual channels

After VC buffer is allowed to transmit its data, maximum of 256 bytes are extracted from the buffer. Then, data is packed into a data frame with header of 4 bytes and trailer of 4 bytes, see Fig. 2. The total data frame length is 264 bytes. Data frame is recoded from bytes to 10-bit sequences by 8b10b codec. After that, the frame is transmitted bit by bit over link assigned with another switch or receiver device.

There are several VCs into output port, hence, there may be conflicts while trying to transfer data from several VCs buffers at the same time. Consequently, data transmission is determined by the Precedence coefficient. This coefficient is determined by two configuration parameters [1, 2]:

- priority level N. There are at least 4 levels from 0 (the highest) to 3 (the lowest);
- Normalized Expected Bandwidth – link bandwidth that VC is expected to use as a proportion of the overall link bandwidth. Normalized Expected Bandwidth is from 0 to 1.

To determine one VC from all others to send data through output port, Precedence is calculated for each VC. In general case, this calculation occurs periodically after sending data frame. Detailed description of the rules for calculating Precedence can be found in [1], [2]. We note here only the basic one: if two or more VCs with the same priority level are ready to send data and they are scheduled for the same time-slot, then VC with the highest Precedence will send data. Then, Precedence is recalculated for every VC. Precedence also depends on bandwidth credit. The bandwidth credit demonstrates intensity of previous data transmission on this

VC. After some time of data transmission Precedence will be recalculated and may take a value less than the initial one. Then, Precedence will be recalculated again and may get the original value or even higher. Hence, Precedence is dynamic priority. Example of dynamic changing of Precedence is shown at Fig. 3.

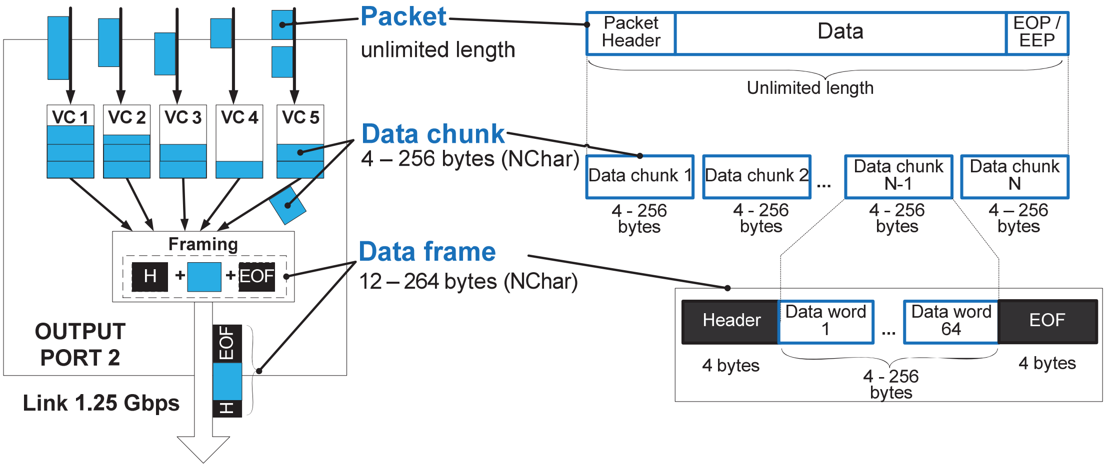

Fig. 2. Simplified format of SpaceFibre data

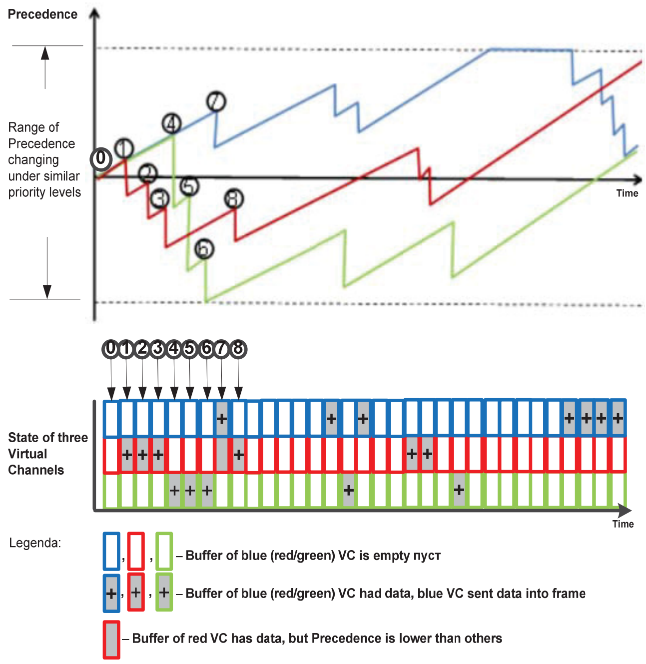

Fig. 3. Example of dynamic changing of Precedence

There are 3 VCs with the same priority levels. When a VC has a data frame ready to send and room for a full data frame at the other end of the link, it competes with any other VCs in a similar state, the one with the highest bandwidth credit being allowed to send the next data frame. At points (1), (2) and (3) the red VC has data to send and sends frames. At points (4), (5) and (6) the green VC has data to send and sends a data frame. At point (7) both the blue and the red VCs have data to send. The blue VC wins since it has the highest bandwidth credit count. After this the red VC is allowed to send a further data frame at point (8).

If the bandwidth credit counter reaches the minimum possible bandwidth credit value, it indicates that it is using more bandwidth than expected and a possible error may be flagged. This condition may be used to stop the VC sending any more data until it recovers some bandwidth credit, to help with "babbling idiot" protection.

Similarly if the bandwidth credit counter stays at the maximum possible bandwidth credit value for a relatively long period of time, the VC is using less bandwidth than expected and this condition can be flagged to indicate a possible error.

There is a schedule for every VC. Schedule consists of list of time-slots. Some time-slots of schedule are marked as enabled to send data from VC1, other time-slots are marked to send data from others VCs. Schedule is determined by: quantity of time-slots, list of enabled/disabled for transmission time-slots, duration of one time-slot. Duration of time slots is always the same for all VCs in schedule. An example of schedule and scheduled packet transmission is shown in Fig. 4.

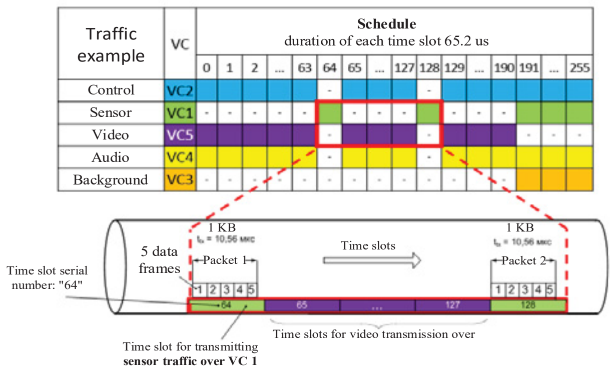

Fig. 4. Example of sensor and video traffic transmission via VC1 according to the schedule

Data reception is started when input port send FCT to the remote side. FCT means that there is a free space in VC buffer on the receiving side to receive a data frame with length of 264 bytes. Then, packet as sequence of data frames is transmitted over link bit-by-bit. At this time, input port of receiving device will receive bits. 10 bit sequences are formed from the bits. Then, data frame or service word is assembled from them. Data frame or service word is recognized and its type is determined. If a data frame is received, then data is extracted from the frame and stored in VC buffer with the same number as sending VC. Then, data is extracted from VC buffer and leave input port. Packet is assembled from data. After that, packet is processed – destination address is specified.

The output port is determined by destination address and switch matrix. The packet is sent to output port, where whole or part of packet is placed into VC sending buffer. The data sending process starts again, as it was described above.

Before switch starts to operate, configuration parameters should be set for each VC: priority level N, Normalised Expected Bandwidth, Schedule, Idle Time Limit – maximum idle time for VC.

SpaceFibre standard has a Management Information Base that contains special Status parameters. If one of VCs in output port uses less bandwidth of link than expected, timer will be set. Duration of timer is equaled to Idle Time Limit, after which the Status parameter in this VC will be made a record of "Insufficient bandwidth usage". Otherwise, status will be "Overuse of bandwidth".

B. *Management of link usage by virtual channels*

Mentioned statuses of VC may be indicated due to malfunction of on-board network caused severe operating conditions of spacecraft. For example, one port of a switch may be failed. Data flows will be redirected to another operated port. As a result, bandwidth of operated port may not be enough to transfer all data. In papers [3, 4, 5], to solve this problem, Adaptive Data Streaming Service (ADSS) was proposed. ADSS allows to monitor of VC status and manage of link usage between VCs by changing configuration parameters: assigned time-slots in schedules, priority levels, etc. ADSS allows to improve efficiency of data transmission for idle VC with “Insufficient bandwidth usage” status. Let us consider in details the management of link usage.

ADSS periodically checks status of VCs. If an idle VC is detected, ADSS will assign this VC to the least busy time-slot. Priority levels of idle VC and VC, which share time-slot to the idle VC, may be changed. Priority levels changes are necessary to allow idle VC use bandwidth of outside time-slot, when no data to be sent from VC originally assigned to the shared time-slot (there is wasted bandwidth). To avoid wasted bandwidth Idle VC will be set to high priority level (Precedence will be the highest), another VC – low priority. As a result, Idle VC will use whole bandwidth of shared time-slot. Fig. 5 is demonstrated this situation: Idle VC is VC5, VC1 has no enough data to use whole bandwidth of shared time-slot #186.

Otherwise, virtual channels will compete with each other for sending data over link during shared time-slot. VC originally assigned to shared time-slot may be enabled to transmit data. It may cause unacceptable delay for Idle VC (Fig.6).

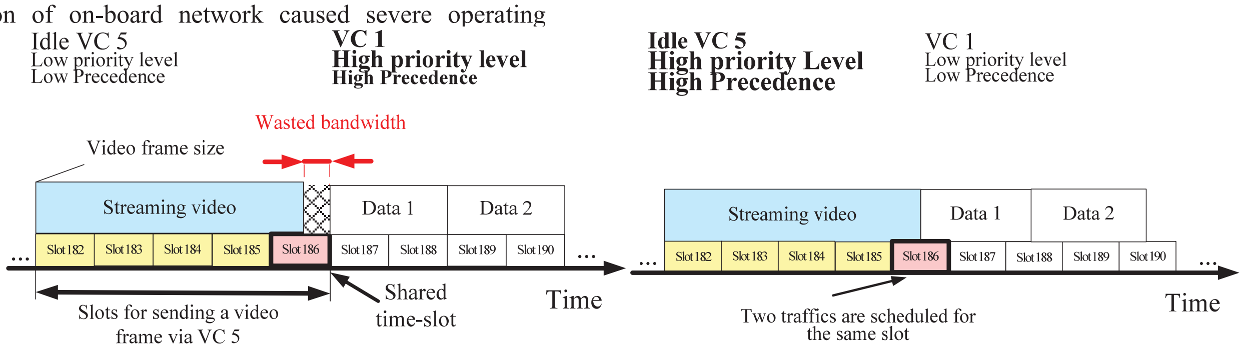

Fig. 5. Assigning an idle VC to someone else's time slot with adjusting priorities

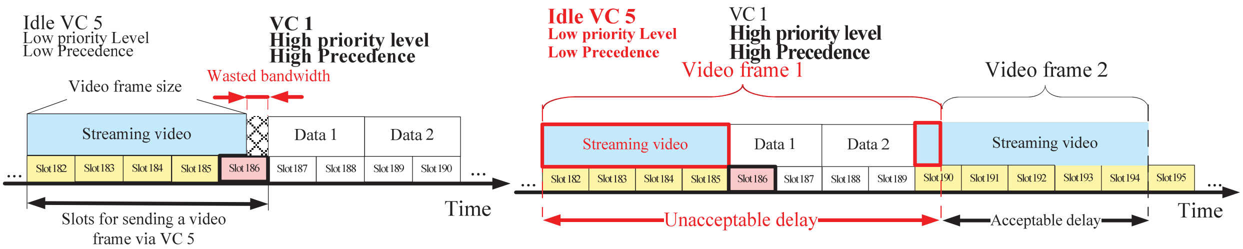

Fig. 6. Assigning an idle VC to someone else's time slot without adjusting priorities

Result of ADSS's operations is new schedule and priority levels. ADSS will generate a reconfiguration request at some point of time. The request will cause to load new priority levels and schedule into internal registers of switch. Then, Precedence will be recalculated (see “Loading new config. parameters” input-block in Fig. 7). If new priority levels might ruin original data transmission logic, then ADSS will re-generate reconfiguration request and return the original priority levels and/or schedule. Consequently, ADSS can dynamically temporarily change SpaceFibre configuration parameters.

Generalized algorithm of data transmission through virtual channels of SpaceFibre switch was developed. It consists of the following steps:

1) Loading initial configuration parameters for all VCs.

2) Calculation of Precedence for all VCs.

3) Updating status for all VCs.

4) Exit if shutdown signal is received.

5) Reconfiguring parameters of VC – loading of new configuration options (schedule(s), priority levels), recalculating of Precedence if it is necessary.

6) Virtual Channels are polled to find at least one VC which is ready to send data. If there is no ready VC, timer for waiting ready VC is started. When timer is expired, go to step 2. If one or more VCs are detected to be ready for data transmission and timer is not expired, then Precedence will be recalculated (step 2 will be called) and, then, step 7 will be performed immediately. If polling (at the begin of step 6) is detected ready VC, then go to step 7 immediately.

7) Transmitting data frame. For this purpose VC with the highest Precedence is selected to send a data frame. Go to step 2.

The algorithm with more details is shown in Fig. 7

To diagnose incorrect functioning of switch the list of all correct control stimuli should be determined. For this purpose we needed to design the finite state machine of the virtual channels operating to data transfer. We used IDEF3 technology [6, 7] to design PFDD diagram of technological process of data transmission through virtual channels. PFDD diagram was based on the algorithm (Fig.7). Then, we constructed OSTN diagram based on the PFDD diagram. OSTN diagram determines the virtual channels operating states of SpaceFibre switch's output port [8]. To find all correct control stimuli the analysis of the states was done. It is presented in the next section.

C. *Analysis of the virtual channels operating states of SpaceFibre switch's output port*

This analysis is based on the researches from [9], [10]. OSTN diagram may be represented as the finite state machine.

The finite state machine [11, 12] describes data transmission over virtual channels into SpaceFibre switch's output port. It is shown in Fig. 8. The states are:

- C1 – waiting for virtual channel will be ready.
  If necessary, new or original configuration parameters are loaded, actions from step 2 to step 6 of the algorithm are performed.
- C2 – ADSS management of link usage for Idle VC.
  Estimates of time-slots, detects time-slot(s) for sharing with Idle VC(s). If necessary, new priority levels will be determined. Also, time point for set new schedule(s) and/or priority level(s) or return original parameters is defined; reconfigures virtual channel(s) with new or original parameters.
- C3 – idle waiting for virtual channel will be ready.
  This state is the same as C1 with the following difference: there is at least one VC with "Insufficient use of bandwidth" status.
- C4 – Data transfer from virtual channel buffer to link.
  Steps are performed according to step 7 of the algorithm.

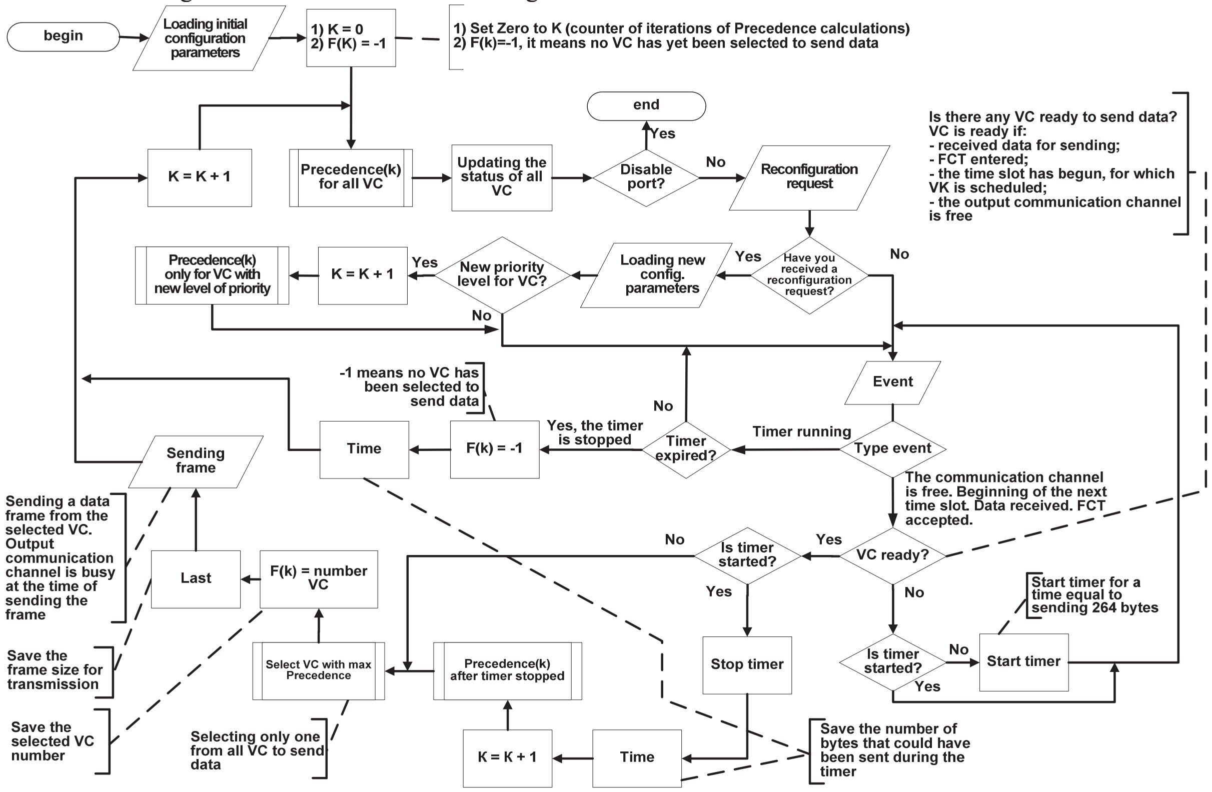

Fig. 7. Diagram of the algorithm for sending data through SpaceFibre virtual channels

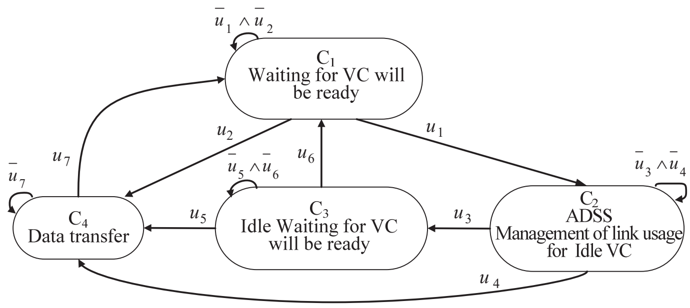

Fig. 8. Finite state machine of operating of virtual channels of SpaceFibre switch's output port with ADSS

The transitions of the finite state machine:

- $C_1 \rightarrow C_2$ – VC was detected that is not ready to send data and it has "Insufficient use of bandwidth" status.
- $C_1 \rightarrow C_4$ – VC was detected that is ready to send data.
- $C_2 \rightarrow C_3$ – ADSS management is impossible or ADSS management has been completed, but there is no VC ready to send data.
- $C_2 \rightarrow C_4$ – ADSS management was successfully completed, VC was detected that is ready to send data.
- $C_3 \rightarrow C_1$ – event (example, port reset) was occurred. It is caused all statuses were updated, there are no VCs with "Insufficient use of bandwidth" status.
- $C_3 \rightarrow C_4$ – VC was detected that is ready to send data.
- $C_4 \rightarrow C_1$ – VC (that was ready to send data) with the highest Precedence successfully sent data;
- $C_i \rightarrow C_i$ $\forall$ $i \in \{1, 2, 3, 4\}$ – current state will be saved if there are no signals (events) that transition port from one state to another. Example, virtual channels of SpaceFibre switch's output port will be into C1 state until at least one VC will meet the conditions to be ready to send data or until VC with "Insufficient use of bandwidth" status will be detected.

Boolean vector $x = [x_1, x_2, x_3, x_4]$ is used to describe the operating states of VCs of SpaceFibre switch's output port (henceforth – device). For example, x = [1, 0, 0, 0] means that device is only in state C1. Changing of x is analyzed in discrete time t, $t \in T = \{0, 1, 2, \ldots, N\}$. Time unit is equaled to time (some cycles) to transit device from one state to another. Thus, x(t) is vector of the operating states of device at time t.

Control stimuli that transfer device from one state to another are presented as vector u = [u1, u2, u3, u4, u5, u6, u7]. The number of elements in u is equaled to number of transitions in the finite state machine. The vector u determines the transitions of the finite state machine for any t. Vector u is considered as known to analyze the finite state machine. There are 2^7 combinations of control stimuli for VCs of SpaceFibre switch's output port. If the finite state machine is more detailed, there will be too many stimuli.

Recursive equation is used to describe the state of the finite state machine:

$$x(t+1) = A(u) \cdot x(t), x(0) = x_0, \quad (1)$$

where x_0 is vector of initial states of device, A(u) is matrix of transition states that depends on u stimuli. According to Fig. 8, matrix is:

$$A(u) = \begin{bmatrix} \overline{u}_1 \wedge \overline{u}_2 & 0 & u_6 & u_7 \\ u_1 & \overline{u}_3 \wedge \overline{u}_4 & 0 & 0 \\ 0 & u_3 & \overline{u}_5 \wedge \overline{u}_6 & 0 \\ u_2 & u_4 & u_5 & \overline{u}_7 \end{bmatrix} \quad (2)$$

The matrix A(u) is stochastic. Transitions of the finite state machine will be stationary. It will occur periodically or permanent.

The task of analyzing of the operating state of the VCs of SpaceFibre switch's output port is to find control stimuli vectors corresponded to the correct port work without analyzing of all possible stimuli. The correct port work is port work without idle (C_3 state). x(t) is described the states of port into time t. x(t) is calculated as solution of recurrent equations by the formula:

$$x(t) = A^t(u) \cdot x(0) \quad (3)$$

The initial data for the analysis are [9, 10]:

1) Initial states x(0) = [1, 0, 0, 0], which corresponds to the start state of VCs of SpaceFibre switch's output port.

2) Correct situation is a situation in which only one element into the vector x(t) is equal to 1. All other cases are incorrect situations – incorrect behavior of SpaceFibre VCs.

3) The number of steps in the analysis must not be less than the number of states.

According to logic of SpaceFibre device operatin, there are mutually exclusive transitions, which cannot be simultaneously: C1 → C2 and C1 → C4; C2 → C3 and C2 → C4; C3 → C1 and C3 → C4.

There are stimuli which cause correct and cyclic work of SpaceFibre device, presented below.

Cycle C1-C4 when u = [0, 1, *, *, *, *, 1], where * is value equaled to 1 or 0. It describes ideal transfer of data without ADSS management. 2^4 of 2^7 stimuli will lead to this correct cyclic situation. Table I shows changing of states of the finite state machine.

TABLE I. THE FINITE STATE MACHINE UNDER U = [0, 1, 0, 1, 1, 1, 1]

States	Finite State Machine step by step							
	1	2	1	4	1	6	1	8
x_1	1	0	1	0	1	0	1	0
x_2	0	0	0	0	0	0	0	0
x_3	0	0	0	0	0	0	0	0
x_4	0	1	0	1	0	1	0	1

Cycle C1-C2-C3 when u = [1, 0, 1, 0, 0, 1, *]. There are 2^2 stimuli combinations for this situation. The situation is long-term inability to transmit data, alternating with events that transit VCs to the initial state. The situation is occurred, when, for example, not issued FCT from remote side. As a result VCs could not send data and VCs became idle. Then, VCs will get "Insufficient use of bandwidth" status. ADSS management could not improve this situation, because remote side is not ready to arrive data (no FCT was issued). In some time event (example, reset) will transit VCs into the initial states. Then, the situation will be repeated. Example is shown in Table II.

TABLE II. THE FINITE STATE MACHINE UNDER U = [1, 0, 1, 0, 0, 1, 1]

States	Finite State Machine step by step							
	1	2	1	4	1	6	1	8
x_1	1	0	0	1	0	0	1	0
x_2	0	1	0	0	1	0	0	1
x_3	0	0	1	0	0	1	0	0
x_4	0	0	0	0	0	0	0	0

Cycle C1-C2-C3-C4 when u = [1, 0, 1, 0, 1, 0, 1]. u is single vector of control stimuli. Table III demonstrates data transmission with idle, ADSS management is impossible.

TABLE III. THE FINITE STATE MACHINE UNDER U = [1, 0, 1, 0, 1, 0, 1]

States	Finite State Machine step by step							
	1	2	1	4	1	6	1	8
x_1	1	0	0	0	1	0	0	0
x_2	0	1	0	0	0	1	0	0
x_3	0	0	1	0	0	0	1	0
x_4	0	0	0	1	0	0	0	1

Cycle C1-C2-C4 when u = [1, 0, 0, 1, *, *, 1]. There are 2^2 stimuli combinations of this situation. Table IV demonstrates data transfer without idle time, ADSS management is performed successfully.

TABLE IV. THE FINITE STATE MACHINE UNDER U = [1, 0, 0, 1, 1, 0, 1]

States	Finite State Machine step by step							
	1	2	3	4	5	6	7	8
x_1	1	0	0	1	0	0	1	0
x_2	0	1	0	0	1	0	0	1
x_3	0	0	0	0	0	0	0	0
x_4	0	0	1	0	0	1	0	0

The described control stimuli are correct, because they do not violate SpaceFibre specification. Moreover, there are correct "permanent" situations with the following stimuli:

- C_1 when u = [0, 0, *, *, *, *, *] – total 2^5 stimuli combinations;
- C_2 when u = [1, 0, 0, 0, *, *, *] – total 2^3;
- C_3 when u = [1, 0, 1, 0, 0, 0, *] – total 2^1;
- C_4 when u = [1, 0, 1, 0, 1, 0, 0], [1, 0, 0, 1, *, *, 0] and [0, 1, 1, *, *, *, 0] – total 13 stimuli combinations.

The total number of acceptable stimuli is 86 for the finite state machine of 4 states (see Fig.8). Other stimuli (42 combinations) will lead to incorrect operations of virtual channels of SpaceFibre switch's output port.

D. *Computer simulation*

Computer simulation of work of the finite state machine of VCs of SpaceFibre switch's output port was done. Program was developed in MatLab. It includes recurrent equations (1) and (3). All necessary calculations were also performed in the program. Computer simulation results are confirmed the results from analysis

When u = [1, 0, 0, 1, 1, 1, 1], there is cycle C1-C2-C4. It demonstrates successful data transmission with idle VC "Insufficient bandwidth use" status. To avoid this status ADSS worked successfully (Fig. 9, a). When u = [1, 0, 1, 1, 1, 1, 1], incorrect situation are arised at the second and further steps - the finite state machine is occurred into two states simultaneously (Fig. 9, b).

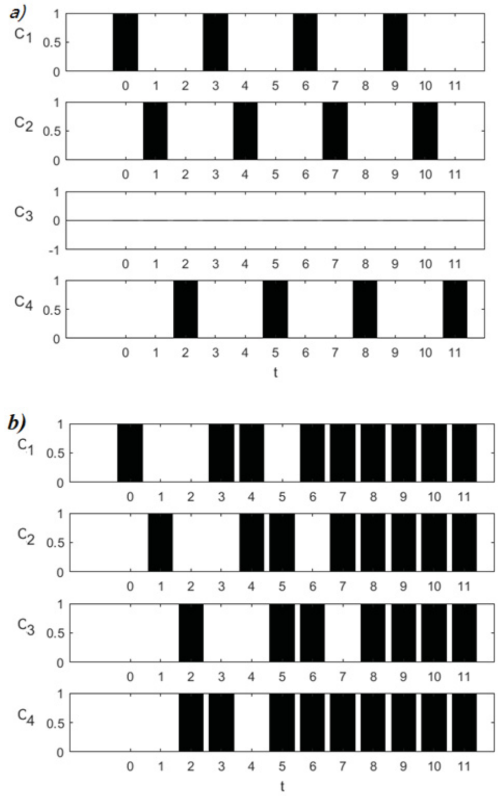

Fig. 9. Operating states changing of the finite state machine within 12 steps of computer simulation with stimuli: u = [1, 0, 0, 1, 1, 1, 1] (a), u = [1, 0, 0, 1, 1, 1, 1] (b)

II. CONCLUSION

This paper describes the task of diagnosing the fails of SpaceFibre switch. SpaceFibre switch is important to keep spacecraft operational, because it is responsible for communications between onboard systems. We considered only data transmissions through virtual channels with Medium Access Control (QoS). Data transmission is performed by using Adaptive Data Streaming Service (ADSS), which allows to manage bandwidth of idle virtual channels. The algorithm of data transmission through virtual channels of SpaceFibre switch was presented in the paper.

To diagnose incorrect functioning of SpaceFibre switch the list of all correct control stimuli should be identified. Control stimuli define virtual channels behavior. If control stimuli that are not included in this list are detected into spacecraft equipment, then failures will be occurred into SpaceFibre switch. The finite state machine of operating states of SpaceFibre virtual channels was developed to analyze the correct functioning of SpaceFibre switch. This finite state machine is based on presented algorithm of data transmission through virtual channels. We carried out the analysis of the finite state machine. As a result, we identified the control stimuli that caused the correct and incorrect operations of SpaceFibre switch. It is done without using full enumeration of all possible control stimuli (it could be too much in real complex spacecraft equipment).

We combined the given correct stimuli into three sets. The first set of stimuli consists of 23 stimuli vectors. They cause periodic correct situation of virtual channel operations. The second set of stimuli – 63 stimuli vectors – leads to permanent correct situations when virtual channels will be only in one state. The third set – 42 stimuli vectors – transits the finite state machine into incorrect states of virtual channels of SpaceFibre switch's output port.

Computer simulation on MATLAB was performed to confirm the given results.

The found correct stimuli make it possible to quickly diagnose SpaceFibre switch operational into spacecraft – it operates correctly or it is malfunctioned.

ACKNOWLEDGMENT

The research leading to these results has received funding from the Ministry of Education and Science of the Russian Federation within the project part of the federal assignment under contract N 8.4048.2017/4.6 from 31.05.2017.

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