An Analysis of Approaches to Onboard Networks Design

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***Abstract*—This paper presents a comparison of several approaches to design of data exchange networks for onboard real-time information and control systems (RT ICS). The approaches considered are based on Fibre Channel (FC), Avionics Full Duplex Ethernet (AFDX) and Software-Defined Networking (SDN) technologies. The networks are compared according to the following criteria: ability to guarantee real-time messages transfer; ability to maintain common time in the system; amount of extra hardware resources to ensure the necessary reliability; support for dynamic (during the RT ICS runtime) alteration of message transfer routes.**

Keywords—real-time systems; onboard networks; fibre channel; software-defined networks

I. INTRODUCTION

In real-time information and control systems (RT ICS), tasks execution and messages transfer must be performed in strictly defined time intervals. Violation of these intervals leads to RT ICS inoperability. To aircraft onboard RT ICS, besides timing constraints, constraints on weight and dimensions are applied, as well as increased reliability requirements.

Traditionally, point-to-point channels and multiple access channels with centralized control were employed to perform data exchange in onboard RT ICS. This practice resulted in growth of the number of data exchange links according to growth of the number of functional units and subsystems of the aircraft, as well as to increase of requirements to speed and reliability of data transfer. Usage of copper cable for the physical links constrained the onboard network bandwidth and resulted in growth of weight and dimensions of RT ICS. Furthermore, cable shielding was required to protect the network from electromagnetic interference, which led to additional increase of the network weight.

One of the promising approaches to reduction of the number of physical data exchange links is usage of switched data exchange networks based on packet switching. To increase the network bandwidth it is reasonable to widely use optical channels which are by order of magnitude lighter than copper ones and are insensitive to electromagnetic interference.

In this paper we present a comparison of approaches to onboard switched networks design based on Fibre Channel (FC), Avionics Full Duplex Ethernet (AFDX) and Software-Defined Networking (SDN). The networks are compared according to the following criteria:

1) Ability to guarantee real-time messages transfer. This criterion is described in the next section in terms of Service Level Agreement (SLA) requirements.
2) Ability to maintain common time in the system.
3) Amount of extra hardware resources to ensure the necessary reliability.
4) Support for dynamic (during the RT ICS runtime) alteration of message transfer routes without violation of SLA requirements for the other messages.

To ensure the data transfer reliability, it is necessary that two non-intersecting routes for each message are present in the onboard network. For most modern RT ICS this equals to duplication of every physical data exchange channel [1, 2].

Possibility to dynamically alter the message transfer routes is determined by the extent to which the routing tables in the switches can be modified in runtime. In some cases these tables can be modified only before start of RT ICS operation; in other cases, the modification can be performed during the system operation.

Dynamic alteration of message transfer routes is necessary in cases of:

- network equipment and/or computational units failure;
- tasks migration during the RT ICS mode change.

Different RT ICS operation modes involve execution of different, but possibly intersecting, sets of tasks. Tasks migration is relevant for integrated RT ICS in which a common pool of computational resources is shared between different subsystems. Support for tasks migration increases the efficiency of computational resources utilization.

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II. DATA FLOWS IN THE ONBOARD NETWORK

Data flows between network nodes are specified as a set of messages $MSG=\{msg\}$. For each message the following attributes are defined:

- $size_{msg}$ – message size;
- for periodic messages: T_{msg} – period of message transfer; for irregular (aperiodic) messages: $\{(s_{msg}, f_{msg})\}$ – set of deadline intervals;
- $src_{msg} \in A$ – message sender node (A is the set of all onboard network nodes);
- $\{dst_{msg}\} \subset A$ – set of message receiver nodes;
- J_{msg} – message generation jitter, i.e. fluctuation range for the message generation time in relation to some reference time within the message period or deadline interval.

Message generation jitter emerges because the execution time of the message's source task depends on the values of its input data.

For each message the following SLA requirements are specified to guarantee real time message transfer: For each message the following SLA requirements are specified to guarantee real time message transfer:

- for periodic messages: the message must be transferred no less than once per its period; for irregular messages: the message must be transferred no less than once per each deadline interval;
- τ_{msg} – maximum allowed message transfer latency (duration between message generation on the sender node and message arrival to all receiver nodes);
- J^*_{msg} – maximum allowed message transfer jitter (difference between the maximum and minimum message transfer latencies).

III. AFDX NETWORKS

The Avionics Full Duplex Ethernet (AFDX) standard [3] specifies onboard network design based on the Ethernet 802.3 specification with some modifications to achieve real time operation. According to AFDX, the network consists of the following elements:

- *nodes* which exchange messages;
- *end systems* which provide interface between the nodes and the network;
- *packet switches* connected by data transfer links.

Meeting the constraints on message passing latency in AFDX networks is achieved by allocation of guaranteed bandwidth to connections between pairs of end systems. Such connection can pass through several packet switches and data transfer links. In AFDX, the connection between end systems is referred to as *virtual link*. All data exchange between nodes is performed through virtual links; routes of these links in the physical network are defined in advance. For each virtual link there is one sender end system and one or more receiver end systems. Several nodes connected to the sender end system can send data through the same virtual link.

Reliability of data transfer through an AFDX network is provided by physical sparing. Each end system is connected to two identical independent AFDX networks. The frames are sent to both networks (in each network the frame follows identical routes). If a frame transfer error is detected in one of the networks (e.g. the received frame has incorrect checksum), the duplicate frame is taken from the other network, where there was no error. The receiver end system checks the integrity of the frames, and if a frame was already received from one network, the duplicate frame is discarded.

Routing tables for the AFDX switch are configured for a static set of virtual links defined in advance and covering the set of RT ICS operation modes. Besides routing, AFDX switches perform traffic management and filtering. Filtering includes checking the correctness of frames transfer sequence as well as verification of frames integrity. Traffic management provides guaranteed bandwidth for every virtual link and does not allow the nodes to exceed the bandwidth. To perform traffic shaping in AFDX, the token bucket algorithm is utilized [4]. Bandwidth for each virtual link is specified during the switch configuration before the start of RT ICS operation. Therefore the routing settings for AFDX network, including virtual link routes and bandwidth allocation, are fixed during the RT ICS runtime, and the standard provides no option to dynamically modify the routing tables.

Upon arrival to the sender end system, the messages from a node are split into frames in the link layer; the frames are placed in the appropriate virtual link's queue and then transmitted into the physical data transfer link. Duration of a time interval between consequent frames of the same message (i.e. for the same virtual link) cannot be less than a specific lower bound.

To ensure data transfer determinism, following attributes are specified for a virtual link:

- minimum duration (start to start) between sending of consequent frames into the same virtual link;
- maximum frame size;
- maximum transfer jitter between two consequent frames.

It should be noted that AFDX only accounts for jitter between two consequent frames (of the same virtual link) and does not account for message generation jitter within the message's period. For instance, in the paper [5] a technique is presented for calculating the virtual link attributes according to data flow parameters and constraints on maximum message transfer latency. The paper assumes strictly periodic generation of messages. Operation with irregular messages in

AFDX networks, as well as accounting for message generation jitter J_{msg} within the message period, is not considered.

IV. FIBRE CHANNEL NETWORKS

Fibre Channel (FC) standard [6] specifies data exchange protocols for high speed (1 to 20 Gbit/s) data exchange networks. This standard supports the following network topologies: point-to-point, arbitrated loop, switched fabric. In this paper we consider switched fabric topology for RT ICS networks, as point-to-point topology is not suitable for complex onboard networks, and FC arbitrated loop does not support concurrent data exchange between several pairs of nodes.

Let us consider a simplest switched fabric network consisting of a single direct switch and a set of nodes connected to the switch (star physical topology). The statements made below can be generalized for a fabric of multiple switches.

There are following existing approaches to provide guaranteed timings for data transfer over FC network:

1) Master-slave approach in which a single dedicated node supervises data exchange in the network [7]. All the slave nodes transmit data only by command from this master node. This approach guarantees exchange determinism but leads to inefficient utilization of the network bandwidth, as at any time instant only a single pair of nodes can exchange data.

2) Time shared access of nodes to the network according to a static schedule [8]. For each network node there is a data transfer schedule; the schedules are coordinated to avoid access collisions. A node can start data transfer only at time instants specified in the schedule. All nodes have synchronized clocks. The set of schedules allows concurrent data exchange between non-intersecting pairs of nodes. This approach utilizes the inherent concurrency of the FC switched fabric to greater extent than the first one, however is does not support bandwidth sharing between several data flows from the switch to a single node. Furthermore, this approach is not resilient to schedule violation by a single node, or to generation of abnormal data flows.

3) Virtual link-based traffic management implemented in “Fibre Channel – Real Time” (FC-RT) profile which is considered in detail farther on.

As noted above, the approaches 1 and 2 have several drawbacks. Therefore we will concentrate on the FC-RT approach which in fact introduces to FC networks most of the essential data exchange solutions supported in AFDX standard.

According to the FC-RT profile, data are transferred through virtual links with bandwidth control. As in AFDX, for every virtual link there is a single sender node and one or more receiver nodes. The set of virtual links and their routes is fixed for each RT ICS operation mode, but FC-RT provides support for several virtual link configuration tables (configurations) on nodes and the switch, with transitions between configurations by commands from a dedicated *configuration master* node. Transition of the network to a different configuration (e.g. during RT ICS mode change) is initiated by the configuration master via sending a broadcast message containing the number of the new configuration. Consistency of data exchange through virtual links is not guaranteed during the transition between network configurations.

Use of virtual links in FC-RT enables guaranteed message transfer timings. Like AFDX, FC-RT utilizes the token bucket algorithm for traffic shaping, however on the nodes this algorithm operates with whole messages, not with separate frames. Following traffic control parameters are specified for a virtual link in the FC-RT network configuration:

- maximum message size;
- period of message generation (i.e. by an application task);
- message generation jitter;
- parameters for the token bucket scheme used for credit allocation: bucket volume and filling speed.

In contrast to AFDX, FC-RT does not implement “sparse” transfer of multi-frame messages, in which there are constraints on minimum start-to-start interval between consequent frames of a message. In the standard scheme for message transmission to the FC-RT channel, all frames are transmitted sequentially without delay. Interruption of message transmission from a node by another message (without interruption of current frame transmission) is possible only when the second message has higher priority.

Reliability of data transfer is provided in FC-RT network by using two independent identical networks. In case of frame loss in the primary network, the receiver node uses the duplicate frame received from the secondary network. In case of successful arrival of both frames, the first arrived frame is used and the second one is discarded.

To support irregular messages in FC-RT, the priority system can be used. Low priority irregular messages do not interfere with data exchange through virtual links, but the transmission latencies for such messages are hardly predictable. High priorities can be assigned to urgent irregular messages, however transmission of such messages can break data exchange through virtual links.

The FC-RT profile provides a service for time synchronization between the network nodes.

V. SDN NETWORKS

The essence of Software-Defined Networking (SDN) approach is separation of data transfer management (Control Plane) and data transfer itself (Data Plane) in the networked devices. Data transfer is managed from a specific center [9, 10].

One of the approaches to SDN implementation is based on the OpenFlow protocol [11]. In terms of OpenFlow, the network consists of (a) switches responsible for packets transfer according to the routing and switching rules stored in the flow tables, (b) the controller responsible for centralized generation of rules and their transfer to all controlled switches, (c) physical data transfer links, and (d) optional dedicated physical links between the switches and the controller. If no dedicated links are present, regular data transfer links are used to exchange data between the switches and the controller.

The controller itself only provides a layer for interaction with the switches via OpenFlow protocol; network management and rules generation is essentially performed by the applications running on the controller.

The OpenFlow network operates as follows. First packet of each new data flow (or a session) is sent to the controller by the boundary switch (i.e. the first switch of the network to receive the packet), as there is no corresponding record in the flow table of the boundary switch. The controller produces the necessary set of rules for the given flow and sends this set to the switches. All subsequent packets of the same flow are processed by switches according to these rules, bypassing the controller. This operation mode is called active. In the passive mode all rules are stored on the switches in advance and no additional processing on the controller is performed.

In order to manage the onboard network according to SDN/OpenFlow approach, the controller must run a dedicated network application which implements following principles of network control:

- In passive mode the application produces and loads the necessary rule sets to the switches in advance, according to SLA requirements specified for the messages. To ensure data transfer reliability, the rule sets must provide two non-intersecting routes for each message. A message is transferred by the secondary route only in case of transfer errors on the primary route, or to provide redundant transfer, in which case several copies of the message are delivered by different routes. It is not strictly necessary to duplicate the whole network to support redundant transfer; the sufficient solution is to provide at least two non-intersecting routes for each message.
- In active mode each message (whole or header only) is processed by the application running on the controller. The application monitors fulfillment of the SLA requirements (message size, period or deadline interval, jitter, addresses of receiver nodes) and reorders the messages if necessary. The main workload in this mode is assigned to the controller which may become a performance bottleneck. However, according to the analysis presented in [12, 13], the performance of OpenFlow controllers is sufficient for processing the messages transferred with frequencies typical for onboard networks. Furthermore, in some cases there is no need for continuous processing of messages on the controller, as it is sufficient to configure the rules on the switch in order to enable it to check the messages arrival frequency for the given data flows.

Presence of the centralized controller enables dynamic reconfiguration of the network in case of RT ICS operation mode change.

In active network operation mode, a failure of the controller or a link connecting the controller to a switch leads to a failure of the whole network operation. So if the network operates in active mode, duplication of the controller and the links connecting the controller to the switches is critical for reliability of data transfer. If some of the “regular” data transfer links are used to connect the controller to the switches, and there are no alternate routes, these links also must be duplicated.

To maintain unified time on the network nodes, the controller can regularly send time synchronization information to the nodes, e.g. according to PTP (Precision Time Protocol).

As the data flows for most of onboard RT ICS operation modes are predictable or even predefined, passive controller mode looks preferable for onboard SDN networks. Ultimately, in this mode the controller application responsible for configuring the OpenFlow switches must perform following activities:

- construction of the routes for message transfer between network nodes to provide the necessary quality of service, including predictable transfer latency and jitter;
- dynamic adaptation of the routes in case of network failures;
- generation of rules for switches, including:
    - rules for checking the traffic for conformance to the SLA requirements;
    - routing rules;
    - rules for distribution of network bandwidth between data flows.

Another approach to application of SDN technology to onboard networks is integration of AFDX or FC-RT networks with OpenFlow networks to enable dynamic management of switches. In this case there is no need to control the message transfer timings on the OpenFlow controller.

VI. CONSLUSION

Table I presents a comparison of three above mentioned approaches to design of onboard switched networks. The set of requirements met by a specific approach determines the class of RT ICS to which the approach is applicable.

TABLE I. COMPARISON OF APPROACHES TO DESIGN OF ONBOARD SWITCHED NETWORKS

Requirement to the network	**AFDX**	**Fibre Channel**	**SDN/ OpenFlow**
Support for periodic messages	+	+	+
Support for irregular messages	–	+	+
Ability to maintain common time in the system	–	+	+
Guaranteed maximum transfer latency (τ_{msg})	+	+	+
Guaranteed maximum transfer jitter (J^*_{msg})	for frames only	+	+
Ability to provide reliable data transfer without full duplication of the network	–	–	+ (a)
Support for dynamic alteration of message transfer routes	–	–	+

a. In active operation mode of an SDN/OpenFlow network, duplication of the controller and the links connecting the controller to the switches is necessary.

AFDX and Fibre Channel networks are widely used in RT ICS for modern aircraft. Use of AFDX is limited to civilian aircraft. A specific of AFDX-based RT ICS is presence of only periodic messages (irregular messages must be simulated as periodic ones, leading to bandwidth wasting). FC networks are used in both civilian and military aircraft, including unmanned ones. Like AFDX, FC networks do not support dynamic alteration of message passing routes without total reconfiguration of the network. Therefore, FC networks can be used only in RT ICS for which the set of modes is defined in advance. Applications of SDN networks are not known to the authors of this paper, however this class of networks is potentially applicable to a wider range of RT ICS than AFDX and FC due to higher flexibility.

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