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INTEGRATED ONBOARD NETWORKING FOR IMA2G

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Abstract

The article presents developments of next generation onboard networking for IMA2G that is based on the SpaceWire/GigaSpaceWire networking technology. The IMA2G prospective vision could be further strengthen by its integration with the Zero Maintenance Equipment (ZME) concepts. The article describes the SpaceWire based backbone network as an integral interconnection for IMA2G, gives examples of applying typical avionics subsystems on SpaceWire based interconnection.

1 Introduction

IMA2G should cover broader scope of avionics units and subsystems – not only data computing resources. It should move to distributed computing entity (unlike typically central computing resources in IMA1G), and cover command/control, signal processing, IO resources also . It sets new requirements for an avionics backbone network as the IMA2G integral interconnection. IMA2G backbone network as an integral interconnection should be able to provide all types of traffic in onboard avionics, substituting the separate and heterogeneous sensor busses, data busses, command busses, field busses and sideband signals for time stamps distribution and hard real-time signaling.

As the SCARLETT (SCAlable & ReconfigurabLe Electronics plaTforms and Tools) project, [1] has shown, the AFDX networking technology isn't appropriate to be the IMA2G integrated networking interconnection. With its optimized for throughput architecture and protocols it has poor latency parameters. It doesn't fit requirements of time-critical fast-loop applications where low latency is the predominant requirement. As a result, for such parts of the distributed on-board architecture with low latency & short period requirements, the AFDX networking is reduced to so-called LC-AFDX (Low Capacity AFDX), [2], provided as 'Private' Field-bus – in fact, reduced from scalable switch-based networking back to point-to-point interconnections.

An IMA2G networking technology should support broad scalability in all domains: in number of nodes, in data rates, in throughput, in latency constraints. Scalability should not only give a way for reconfiguration, increase(decrease) number of nodes and integrated avionics resources gain, but support structured isoefficiency in interconnection characteristics also. Packet delivery and signaling latency should be confined in required bounds. Scalability of network integral throughput should be accompanied by statistical equidistance of end nodes and keeping bilateral throughput between them in scaling network structure. It would be vital for true flexibility of function allocation that is claimed to be one of the IMA2G key features. Real-time signaling with strict latency constraints is important for synchronization, control in the loop, control signaling.

2. Integrated Networking for IMA2G

Evolution of integrated modular avionics from IMA1G to IMA2G is transition to integrated architecture on-board systems. Target systems of an aircraft would not be isolated subsystems, with boundaries implemented in hardware and software structure of on-board equipment. They would become virtualised and distributed over on-board equipment structure. On-board processing, data acquisition and communication facilities should form an integral pull of resources for all the set of aircraft on-board systems target tasks.

From autonomous computers in the federative architecture we move to an integrated computing entity for data and signal processing. Logical boundaries between target systems would not be reflected in a structure of on-board processing and communication infrastructure. Further integration in IMA2G should cover data processing in a distributed modular electronics (DME) architecture, as well as command and control, I/O and signalling tasks. DME will have scalable distributed computing by integral computing environment. IO would be separated from computing modules and could be positioned anywhere in the distributed architecture. Real-time constraints in IO signaling and control should not lead to physical binding them to particular modules but could be distributed over the DME structure and could migrate in system reconfiguration. Reconfiguration mechanisms would work in virtually integral computing environment while being physically distributed and spread over the aircraft. These key features should be supported in distributed computer architecture, system software and scalable onboard networking interconnection.

DME on-board architecture should move towards integral interconnection infrastructure, should be supported by an Integrated Communications Network (ICN). It should provide a communication entity that could support all types of traffic in the distributed on-board avionics, Table 1:

- Sensor buses with high-rate data streams between digitized signals sources and receivers;
- Command buses, that needs to deliver command packets with deterministic delivery time;
- Data buses for distributed processing, with low latency delivery of data packets;
- Signal lines with hard real-time signals distribution with ultra-low latency for synchronisation and control.

Table 1. Airborne interconnections

Bussing	Current bussing examples	Prospective alternative
Sensor buses	Fibre Channel (FC)	SpaceWire/ GigaSpaceWire
Command buses	MIL-STD 1553B	SpaceWire, SpaceWire-D, SpaceFibre
Data buses	AFDX (Ethernet), SRIO	SpaceWire, GigaSpaceWire, SpaceFibre
Video buses	ARINC818, FC-AV	SpaceWire, GigaSpaceWire, SpaceFibre
Field buses	SPI, I2C CAN, RS485, RS422	SpaceWire
Time synchronisation busses	Proprietary bussing	SpaceWire
Sideband signals	Proprietary, unit-specific wiring, multiple wires	SpaceWire

The Integrated Networking ARchitecture (INAR) for IMA2G and AZME has been developed, which is based on

SpaceWire/GigaSpaceWire networking technology, [3].

The INAR gives a basis for building scalable networking infrastructure with compact and light-weight routing switches, ready for scalability and duplications for redundancy. It provides high rate communications (up to 400 Mbit/s for SpaceWire, 1-5 Gbit/s for GigaSpaceWire links), better latencies than other networking technologies, efficient and compact implementation in chips.

INAR provides integral network infrastructure for all types of traffic in DME: high-rate data streams, command packets with deterministic delivery time, data packets for distributed processing and IO, common time ticks distribution, ultra-low latency distribution of hard real-time signals. Interfacing INAR to other interconnections (ARINC429, CAN, AFDX, FibreChannel) for gradual evolution of avionics is provided by gateway nodes.

3. INAR networking with the SpaceWire technology

The SpaceWire networking technology development was launched by the ESA initiative and has been done by the international SpaceWire WG that was formed and coordinated by the ESTEC/ESA. The first release of the SpaceWire standard had been published in January 2003 (the current release – 2008, [4]). Nowadays SpaceWire is the mature technology, it is supported by ESA, NASA, Roscosmos, JAXA; it has been used in a number of national satellites and spacecrafts and in international missions, [5].

SpaceWire defines full protocol stack-from physical level to network level (in the accompanying standards – the Transport level also). It uses high-rate serial duplex links channels with low power consumption LVDS signals and automatic transfer rate adaptation with continues scale of rates, 2-400 Mbit/s, high-rate packets switching scalable interconnections with routing switches, tolerant to faults and to intermediate faults protocols. SpaceWire has embedded system functions for real-time distributed architectures: common time codes distribution, distributed interrupt signals. Its components, e.g. SpaceWire NIC in end nodes, is very compact in VLSI implementation and could be integrated into any types of nodes – from computing nodes to simple sensor and actuator chips/SiP. Further SpaceWire technology developments – GigaSpaceWire, [6], SpaceFibre/SpaceWire-RT, give higher rates (1-10 Gbit/s), longer links (to 100-200 m), galvanic isolation, extended QoS features, [7]. GigaSpaceWire defines DC-balanced links with 8B10B coding and galvanic isolation options.

The SpaceWire standard does not set any limitations on the packet size. This feature can be used for support of unpacketized data stream (e.g. raw radar digital signal stream) or large packets for data streams with huge data items (e.g. video frames), in SpaceWire based communication infrastructures for on-board systems. In our design we included ability to, frame the incoming byte stream, supply it with an adequate packet descriptor type, format it as a packet, and send by the link to the network. Thus, we can do an entrance packetizing of a raw data stream. It could be a useful feature to communicate with devices, which has not information flow packetizing facilities inside them.

Another SpaceWire important feature is hard real-time signaling support.

These features correlate well with prospective avionics IMA2G requirements.

Based on SpaceWire spacecraft on-board equipment integrated modular architecture is presented at the Fig.1.

Modern on-board systems use packetized digital streams flows to deliver signals and data to and from sources and receivers. The switched SpaceWire/GigaSpaceWire digital signal links offers:

- increase of a distance from sensors/effectors to ISDS modules up to any reasonable for on-board systems values; it provides broad scope for IMA lay out and placement on board;

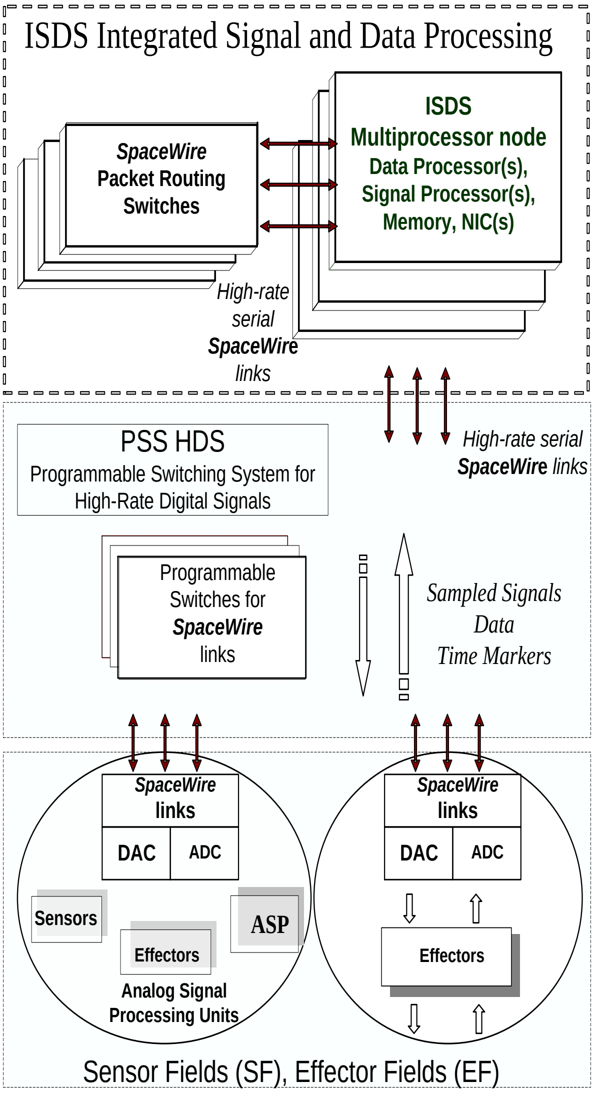

Fig. 1. Distributed Integrated Modular Spacecraft Avionics Architecture

- scalability of sensors/effectors to ISDS channels cumulative throughput;
- reduction in hardware: in wiring, in cables weight, in interface circuitry;
- programmable distribution of high-rate digital signals between sources and recipients, with information flow multiplication, included;
- reconfiguration of links between sensors/effectors and ISDS modules, system fault-tolerance improvement.

GigaSpaceWire is another type of a link in the SpaceWire technology, recently introduced and implemented. GigaSpaceWire provides its easy integration in a SpaceWire network: change the links you need for higher throughput, longer distances or galvanic isolation and use the common SpaceWire network infrastructure elsewhere. The GigaSpaceWire protocol stack introduces new PHY and Symbol layers, modifies the Exchange layer; the SpaceWire Packet and Network layers are used without any changes.

The DS encoding scheme is substituted with the DC-balanced 8b10b encoding which is currently used in a wide number of communication standards. With GigaSpaceWire the link transmission rate can be raised up to 1-2.5 Gbit/s (5 Gbit/s in future), the maximum cable length can be increased to 100 m with cable mass reduced more than twice up to 30 g/m; galvanic isolation can be implemented. Lower rates could be used also in case one has a need just for galvanic isolation or longer distances.

For the integrated network interconnection it is important to support hard real-time signaling also (time ticks for synchronization, interrupts and alarm signals from IO units, urgent control signals to attached equipment, etc.). Packet transfer service doesn't ensure guaranteed low-latency, in microseconds, delivery of such control signals by a message delivery neither in AFDX, nor Fibre Channel, nor 1553B. In SpaceWire packet transfer service is supplemented by specific mechanism of control signals hard real-time delivery, [8]. These control signals are transmitted over the network in some microseconds irrelevant to the load (or overload) of the network links and routs. The SpaceWire Time-code service ensures low-latency delivery of time-stamps; the Distributed Interrupt mechanism provides transmission of system-critical urgent signals and commands, with the receipt confirmation or without it. Latency of a control signal passing a routing switch is 200-300 ns typical; delivery of the signal from the source to any node of the network is proportional to the network graph diameter and for practical network installations is 1-3 mcs.

To ensure high reliability of the signals delivery, the mechanisms provide broadcast transmission, automatic acknowledgment of signal delivery and fault detection, isolation and recovery procedures.

It is supported by the chips - processors and peripheral controllers with embedded SpaceWire and GigaSpaceWire links, [9, 10], Fig. 2.

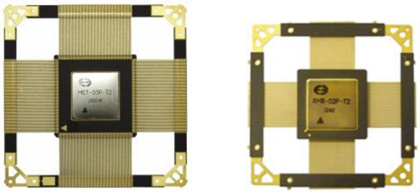

Fig.2 A micropocessor and peripheral controller with embedded SpaceWire/ GigaSpaceWire links

4. System Level Fault-Tolerance with Operated Redundancy

The IMA2G prospective vision could be further strengthened by its integration with the Zero Maintenance Equipment (ZME) concepts, [11]. The ZME is airborne equipment that is designed to automatically recover without personnel intervention for a given time. Avionics that is created with substantial reduction of maintenance efforts gives to airlines undeniable advantages in operating airship cost (approximately 50 %), possibilities of realizing more compact flight timetable and using airports equipped with a low level of surface facilities. Operated redundancy of ZME computing nodes is complemented by system-level fault-tolerance of DME to convert it into ZME IMA2G.

For fault-tolerance support in INAR at the system level the basic SpaceWire technology features are exploited. System-level fault-tolerance is supported by INAR features for building fault-tolerant network infrastructure. INAR provides construction of scalable network interconnection with operated redundancy, adaptive and redundant packets and control signal tokens routing in it. Automatic recovery from transient faults is a native feature of SpaceWire protocols at several layers. Automatic recovery from persistent faults is done by intelligent SpaceWire routing switches. Traffic partitioning ensures protection of packet flows in the network interconnection from spurious coupling between them. Trusted interconnection interface in end-nodes provides protection from end-node applications malfunctioning that could disturb system level operation.

Deterministic model of fault-tolerance, *d*-faultless systems (no-failure operation with up to *d* system components failures) is used to govern INAR fault-tolerant structures development and estimation. Redundant sets of end-nodes – computer modules/CNOR, peripheral modules, IO modules, along with transparent tasks migration to available operating end-nodes, provide system-level operated redundancy.

For fault-tolerance support in ZME at the system level the basic SpaceWire technology features are exploited:

- ✓ automatic detection of a link connection fault or breaking that is built in the Symbol, Exchange levels' protocols;
- ✓ automatic connection recovery after a transient fault in a link;
- ✓ adaptive routing, which is built in the Network level protocol, that provides automatic selection of alternative rout if an initial output port of a routing switch happens to be not connected, faulty or busy on a forwarded packet arrival;
- ✓ fault-tolerance and recovery mechanisms built in the basic SpaceWire protocols for Time-Codes and Distributed Interrupts distribution that know how to pave their ways to any node in the network bypassing failed switches and links;
- ✓ no restrictions whatever on interconnection graph topology that gives full scope for building redundant interconnection topologies of any types;
- ✓ network clusterisation facilities (by regional-logical addressing) that enable communications localization in a region in correlation with easily monitored, controlled (and blocked, in case of a fault propagation risk) packets inter-region transition in dedicated points of clustered interconnection;
- ✓ reconfigurablility of tracing logical connections between nodes by routs alignment in interconnection routing

switches without changes in end nodes logical connections setup.

They are complemented by additional features built in SpaceWire nodes and switches implementations to have full exploitation of these important for fault-tolerance original SpaceWire technology features, to provide no-failure operation at the system level of INAR and ZME avionics.

4.1 Automatic detection of a link connection fault and connection recovery

The SpaceWire standard provides mechanisms to detect single errors at the Link level. Each symbol has the parity bit to detect caused by transient faults single errors. At the Exchange level a symbol sequence is checked and caused by link malfunctioning symbol sequence errors are detected. At this level changes of the D and S lines are checked and their long-duration non-changing is detected as the link failure (open-circuit connection or the link counterpart node failure).

The GigaSpaceWire uses 8B10B encoding that also detects single errors in symbols. At the upper layers symbol sequence errors are detected also (e.g. wrong K-codes in a sequence).

4.2 Adaptive routing

The SpaceWire has adaptive routing mechanisms – associated with a logical address and with an output port number. In the logical address adaptive routing the routing table specifies a list of alternative output ports that could be used for transmission of packets with this logical address; any of the ports could be used for the packet transmission. The particular port number is designated dynamically in the course of the packet routing in correspondence of the listed ports status (ready, busy, failed, etc.). This type of adaptive routing could be used when there are multiple routs between the source and destination nodes, Fig.3.

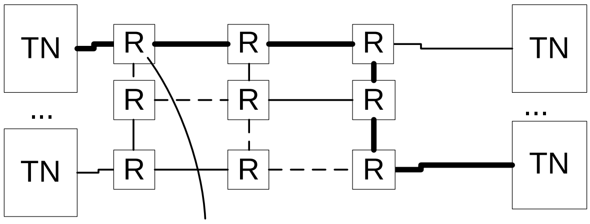

Fig.3 Adaptive routing by routing table

In associated with an output port number adaptive routing a list of alternative output ports is defined without reference to a particular logic address. In this case, in the course of routing an output port is determined by the routing table. Then it is checked if a list of alternative ports is specified for this port; if there is such a list any of them could be selected for the packet forwarding through the router to work around faulty link, to balance links workload, etc. This type of adaptive routing could be efficient in multilink interconnection between adjacent nodes, Fig.4

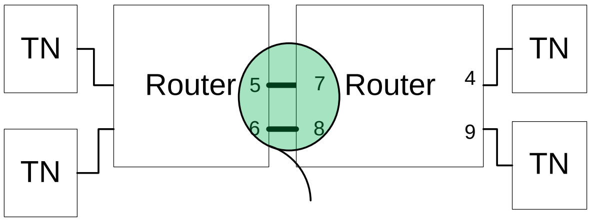

Fig.4 Adaptive routing by port number

Adaptive routing in SpaceWire networks may be used for dynamic by-passing network sections with faults, links with transient errors and disconnections or overloaded ones.

4.3 Reconfigurablility of tracing logical connections between nodes

Packets transfer routes are specified in routing tables of the network nodes – routing switches. The distributed in the nodes' routing tables information specifies routes, by which a packet would be transmitted through the network. Reconfiguration of logical connections through the network would be done by updating routing tables in routing nodes.

4.4 Fault-tolerance and recovery mechanisms in the Time-Codes and Distributed Interrupts distribution

Time-codes are specific codes and mechanism in SpaceWire that are aimed for system time synchronization in terminal nodes. Distributed interrupt codes are aimed for hard real-time signaling in SpaceWire nodes. Due to specific protocols of control codes distribution time-codes and distributed interrupts are spread over a SpaceWire network with very low latencies, which are time-independent to data transmission network load, and reach any node of the network in some microseconds.

The time-codes and distributed interrupt codes (control codes) are distributed in the network by broadcasting and find any possible routes to reach any node on the network. In case of fault in a link or a node the codes will automatically run around and bypass it if the interconnection graph remains a connected graph and there is a potential route in the network structure.

4.5 Redundant interconnection topologies

The SpaceWire standard, its protocols and mechanisms sets no limitations on a network interconnection graph. We can build redundant INAR topologies that ensure reliability, fault tolerance to a specified number of faults of nodes and links in the network.

A network fault tolerance against *n* faults may ensure network persistency that keeps transmission and routing of packets after the faults. It could be afforded by *n+1* duplication of nodes and links. A packet is sent and runs over the network as a single copy. On its run, in case of a fault on its way it would be lost; however, next packets will run around faulty parts, due to redundancy, and the network will keep operating.

For packets that should be delivered even in case of faults, not only the network structure should be duplicated, but the packet transmission also. The packet is sent in multiple copies that should be routed along different routes in the network. Thus a fault in the rout of one packet copy will not kill the packet, as another copy will run by another rout and will not be affected by that fault.

4.6 Network clusterisation

Another important feature is network clusterisation. The SpaceWire has native features for network clusterisation. The so called “regional addressing” gives a way for structuring destination address in a packet, which may include address in the cluster and address of the cluster. The last one specifies a node through which the packet will be forwarded into the cluster. Thus the cluster boundary is known for the system. Additional screening at the cluster border could protect its inward nodes from outward nodes faults and malfunctioning (e.g. bubbling idiot). With the trusted systems component concept, [12], the bridge node of the cluster could control inward and outward packet and control signals flow.

5 Cockpit videostreams distribution network segment example

As an example of an INAR segment consider a videostreams distribution network segment in the cockpit integrated display cluster. Video streams distribution segment provides efficient and robust video data delivery from the videostreams’ sources to the cockpit displays, building task oriented, Cockpit Integrated Display Cluster for IMA2G/ZME.

Conventional videostreams delivery interconnections are built according the ARINC 818 standard that uses FibreChannel (FC) bottom layer for its transport implementation. However analysis of the FC shows that its features don’t correlate well with native videostream frames requirements and lead to superfluous data slicing, processing and synchronization overheads in implementation that are caused by the FC limitations. The recent ARINC 818-2 revision makes this discrepancy more substantial.

Juxtaposing the ARINC 818 and the SpaceWire/GigaSpaceWire features, Table 2, one could see that the SpaceWire networking technology well correlates with the

videostreaming requirements and provides embedded, ready-made mechanisms for its support.
Format of SpaceWire packets makes it easy to package natural video data units into SpaceWire packets. For instance, a video frame, say 2 Mbits/frame, could be packaged in a single SpaceWire packet, without its cutting into fragments, not to break down a display line to pack it into a packet payload field, packing/unpacking them in a separate packet each, etc. It simplifies interfacing video sources/sinks to the network and increases useful throughput for video streams delivery.
Videostrems routing, multicasting or broadcasting from multiple sources to multiple displays are provided by native SpaceWire features and is easily controlled by configuration and dynamic reconfiguration of routing tables in the SpaceWire switches. Thus better workload repartition between Pilot Flying and Non Flying data and more efficient cockpit displays field organisation are achieved.
Redundant topology of the SpaceWire network segment provides fault-tolerance of the video streams distribution. Adaptive routing – a native SpaceWire feature, automatically, on the fly, switches data streams to healthy links bypassing faulty ones without network management system interference.
With redundant interconnection topologies we can ensure fault tolerance to a specified number of faults of nodes and links in the network. At the Fig.5 the cockpit SpaceWire interconnection tolerant to any 2 faults of links and/or nodes is presented.
Network operation recovery after transient faults in links and nodes is embedded in the SpaceWire protocol stack at several layers. It is done automatically by respective FSM in nodes and link controllers.

Table 2. ARINC 818 / 818-2 and SpaceWire/GigaSpaceWire features

ARINC 818	*SpaceWire/ GigaSpaceWire*
High rate serial channels	High rate serial channels with scalable performance
Packetized video data transfer	Packet switching network technology
Correlating packet size (packet payload) with the display line/ image fragment / image size	Arbitrary packet length; can fit any display line/ fragment / image size
Channel Bonding (inverse multiplexing to *k* physical links)	Adaptive routing in a routing switch; automatic inverse multiplexing of a packet stream to *k* output ports
New ARINC 818-2 features	
Bi-directional interfaces (camera – configuring and trimming, display - data from touchscreen, etc.)	Duplex links – the native feature of the SpaceWire/GigaSpace Wire links and routs
Video switching; switching video data streams	Fast packet switching network technology. Programmable routing tables. Low latency wormhole routing.
Video streams multicasting	Multicast support in routing switches

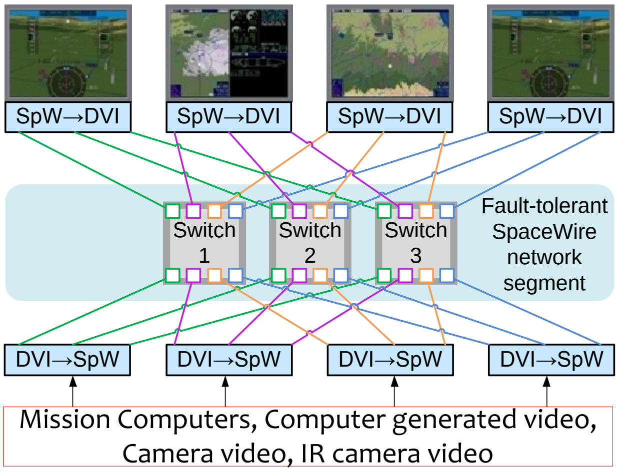

Fig. 5 Fault tolerant fly-by-wire systems; 2 failures tolerant cockpit interconnection

The SpaceWire routing switch is a compact unit, Fig.6, that could be easily placed and installed in aircraft on-board space.

Fig. 6. 16-port SpaceWire routing switch for airborne networks

5 Conclusion

The SpaceWire technology can provide all the necessary IMA2G and ZME features in the frame of common network architecture and basic protocol stack with optimized customization to particular needs and requirements of distributed applications in its segments and clusters. The avionics subsystems prototyping with INAR networking infrastructure has proved its efficiency and conform the IMA2G and ZME requirements. Methodology and tools for INAR-based onboard networks design and configuration has been developed, [13], to support practical design of DME avionics with INAR networking.

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