Table 1. Communication architecture comparison matrix.

Feature	MIL–STD–1553	SAFEbus	TTP/C	FlexRay	TTCAN	IEEE–1394B	SpaceWire	Ethernet 10/100 Base-T	AFDX	Fibre Channel	Gigabit Ethernet
Description	Military standard defining electrical and protocol characteristics for a data bus Centralized messaging control	Backplane bus that is the basis for ARINC 659, a standard for transfer of digital data between line replaceable modules (LRMs) within an integrated modular avionics cabinet Used	TTP governed by TTP/C specification developed by University of Vienna and TTTech Synchronous and fault-tolerant protocol developed for safety-critical, real-time distributed systems	Deterministic and fault-tolerant bus system for high-speed automotive control applications, based on standards developed by FlexRay consortium	TTCAN is an extension to the unchanged CAN protocol, introducing to CAN networks time-triggered communication and systemwide global network time with high-precision TTCAN controllers can be seen as CAN controllers enhanced with a frame synchronization entity TTCAN is internationally standardized as ISO DIS 11898–4	The IEEE 1394 standard enables simple, low-cost, high-bandwidth data interfacing between computers, peripherals, and consumer electronics products.	SpaceWire is based on two existing commercial standards, IEEE–1355 and LVDS, which have been combined and adapted for use onboard spacecraft	The family of LAN products covered by IEEE 802.3 standard that defines what is commonly known as the CSMA/CD protocol	AFDX is a standard that defines the electrical and protocol specifications, (IEEE 802.3 and ARINC 664, Part 7) for the exchange of data between avionics subsystems	Defined by a collection of ANSI standards, a high-bandwidth (100 MB/s) serial communication bus supporting several topologies, protocols, and media	Combines IEEE 802.3 Ethernet CSMA/CD standard with ANSI X3T11 Fibre Channel physical layer specifications
Application	Primarily military aircraft and spacecraft, some commercial	Developed by Honeywell for commercial aircraft	Applicable to all manned vehicles, commercial and military to date	Automotive electronics	Automotive drive-by-wire	Primarily consumer electronics. Has been proposed for automotive and used in aerospace applications	Developed in Europe for use in satellites and spaceborne experiments	Widely used for non-critical LAN applications in all sectors, including aerospace	Developed by Airbus Industries for commercial aircraft	Targeted for use in mass data storage and transport applications for large computing networks SAN standards exist defining use in an AE	Widely used for non-critical LAN/WAN applications in commercial and public sectors
Deployed Systems	*ISS*, Shuttle payloads, military aircraft, and ships	Aircraft information system (AIMS) on Boeing 777	Airbus A380 cabin pressure control Full-authority digital engine control for Aermacchi M–346 and Lockheed Martin F–16 aircraft, railway switching/interlocks	Prototype in-vehicle testing	Concept/prototype automobiles No widely reported deployment in publicly available literature	Widely used in personal computers and peripherals Planned for use in automotive telematics applications Used in JSF and a noncritical Space Shuttle camera system	IEEE 1355-based communication used on several ESA spacecraft, such as Rosetta SpaceWire-like hardware on NASA SWIFT spacecraft Proposed for James Webb Space Telescope and several ESA missions	Nearly all commercial, educational, military, and government facilities Implements *ISS* LAN	Used on Airbus A380 Planned for Boeing 787	Deployed in SANs for commercial computing networks Used in upgrades to existing military avionics Selected for use in Joint Strike Fighter	Nearly all commercial, educational, military, and government facilities
Communication Control Event-/Time-Triggered, etc.	Event-triggered, (command/response) requires bus controller	Time-triggered, based on communication schedules in pre-loaded tables Masterless	Time-triggered, autonomous and independent of host Masterless	Time and event triggered Event messages sent during specified dynamic slots	Time and event triggered (event in arbitrating frame)	Cycle master (root) broadcasts cycle start package For isochronous transmission in broadcast mode Isochronous resource manager arbitrates requested isochronous transfers Any time left used for asynchronous transfers arbitrated by root	Event triggered	Event, employs CSMA/CD for half-duplex implementation	Event-triggered, based on host message generation, bandwidth predefined and guaranteed by hard limits	Event-triggered, based on host message generation and arbitration as required based on topology	Event, employs CSMA/CD

Table 1. Communication architecture comparison matrix (continued).

Feature	MIL–STD–1553	SAFEbus	TTP/C	FlexRay	TTCAN	IEEE–1394B	SpaceWire	Ethernet 10/100 Base-T	AFDX	Fibre Channel	Gigabit Ethernet
Maximum Data Rate (MB/s)	1 MB/s	60 MB/s	5 MB/s using RS–485 phy, 25 MB/s using Ethernet phy	10 MB/s	1 MB/s maximum high-speed CAN: 125 KB/s max for low-speed/fault-tolerant CAN	800 MB/s currently available (3,200 MB/s defined) Limited by cable media and length and the slowest device between transmitting node and receiving node	400 MB/s	100 MB/s (10 MB/s)	100 MB/s using ethernet phy.	1, 2, 4 and 10 GB/s	10 GB/s(1 GB/s)
Message Size	640 bits (512 data bits)	1 to 256 32-bit data words, no overhead in packet, programmable gap from 2 to 9 bits	24 120-bit overhead 2–240 byte data	8-bytes overhead, 0-254 bytes data	Standard: 51 bits overhead Extended: 72 bits overhead; 0-8 bytes data	Based on transmission rate and mode 4,096 bytes asynch. and 8,912 isoch. at 800 MB/s for beta packets	5 bytes overhead, data payload not limited by standard	TCP: 66–118 byte overhead 1,416–1,460 byte data UDP: 53 byte overhead 17–1,471 byte data	53 byte overhead 17–1,471 byte data	2,148 bytes (36 bytes overhead, 4–2,112 bytes payload)	TCP: 66–118 byte overhead 1,416–1,460 byte data UDP: 53 byte overhead 17–1,471 byte data
Message CRC (Yes/No)	No, app. level data CRC	No, not required due to self-checking bus pairs	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Provide All Nodes With Data Transmitted by Other Nodes for Local Node Use as Required	No RT to all, only through broadcast messages, BC to all RT	Yes, must be specified in message table memory	Yes, by default	Yes	No, only nodes with proper message ID filter see particular messages	Using isochronous broadcast only	Can be done via packet distribution at routing switches	No, unless computing node is configured to snoop or data is broadcast (UDP)	Only if all messages sent as broadcast	Multicast with switched fabric only	Multicast with switched fabric only
Duplex	Half	Half	Half	Half	Half	Full, Legacy: Half	Full	Half and full	Full	Full	Half and full for 1 G, Full only for 10 G
Media Access	TDMA, Manchester II	TDMA	TDMA	TDMA for static data and minislottting for dynamic (event) data	TDMA for exclusive windows, with CSMA/CD+AMP in arbitrating windows	Overlapping arbitration and data transfer called BOSS Legacy requires arbitration for transmission via request during specific periods	Flow control via tokens (port credit)	CSMA/CD (collision avoidance) for half-duplex, direct for full-duplex with processing by switch for delivery	Traffic shaping by end system based on VL definition. Filtering (validation) and policing at switch	Flow control based on port credit	CSMA/CD (collision avoidance) for half-duplex, direct for full-duplex with processing by switch for delivery
Media Access Without Arbitration (Yes/No)	Bus master only	Yes	Yes	Yes for static segment, no for dynamic segment	Yes for exclusive windows and no for arbitrating windows.	No	No	No, half-duplex Yes, full-duplex	No	No	No, half-duplex Yes, full-duplex
Clock Synchronization	Available through master command (not required)	Clock synchronization is scheduled and all BIUs participate	Tight synchronization/ fault tolerant	Yes	Level 1 via master reference message Level 2 via global synched clock using data in ref. message	Cycle master handles clock sync. for scheduling isochronous transfers	Not required, but facility for time master exists for time reference	Not required	No	Not required	Not required
Global Time Base (Yes/No)	No	Yes	Yes, fault tolerant, masterless	Yes	Yes, synched to clock master via reference message, backup masters can be present	No	No	No	No	No	No
Latency Jitter	<12 µs for RT response (may be extended to >20 µs)	Goal is <2 bit times	Programmable (1–10 µs)	Programmable, 1–6 µs	<100 µs	<0.02 µs	Variable based on topology, estimated <=10 µs	>=50 µs and variable due to CSMA/CD in half-duplex mode Small, but varies based on size of network and traffic in a switched full-duplex configuration	<=500 µs	Small, but varies based on size of network and traffic	Small, but varies based on size of network and traffic in a switched full-duplex configuration

Table 1. Communication architecture comparison matrix (continued).

Feature	MIL–STD–1553	SAFEbus	TTP/C	FlexRay	TTCAN	IEEE–1394B	SpaceWire	Ethernet 10/100 Base-T	AFDX	Fibre Channel	Gigabit Ethernet
Processor Required at Each Node	Yes for BC No for modules with DMA/glue logic for simple RT	No	Yes	Yes	Could be done with complex VHDL design implemented on an FPGA	Yes	No, only on one end of a point-to-point connection if simple protocol used	Yes	Yes	Yes	Yes
Maximum Number of Nodes on Single Bus	31	32 (theoretical AIMS implementation uses 8–10)	64	64	120	63 on a bus with up to 1,023 buses supported by addressing	224 (logical addresses per cluster) allows regional addressing of 224×224	1 node per segment, 1,024 segments (10/100 Base-T)	Governed by number of switched ports available	127 on arbitrated loop, 224 million logical limit on switched fabric	Governed by number of switched ports available
Physical Layer Length	No limit specified, can be >100 m	<1.5 m (estimate)	Depends on physical layer, 30 nodes on 100-m length for multi-drop topology Cable length of up to 1 km possible	24 m, point-to-point or total bus length	30 m for 1 MB/s	Point-to-point: 4.5 m nominal any type, 50 m over POF at 200 MB/s, 100 m over GOF at 3,200 MB/s, 100 m over CAT5 at 100 MB/s	10 m	100 m between TX/RX	Same as Ethernet 10/100 Base-T	30 m electrical, at least 2 km optical (10 km reported)	1 G:25 m electrical, 5 km optical 10 G: 40 km optical
Physical Layer Independent (Yes/no)	No	No	Yes	No, has physical layer spec.	No	No, 1394 phy. controller required.	No	No	No	No	No
Implementation Physical Layer	Electrical characteristics defined by standard as twisted pair or coax, can be transformer coupled	IEEE 1194.1, copper	Currently RS–485 (MFM) or Ethernet phy. (MII) using COTS devices. Custom over optical fiber.	Twisted pair	CAN controller supporting TTCAN level 1 or 2 with CAN transceiver and twisted pair	1394 physical layer controller or phy./link controller. Requires additional external transceivers for optical connections	LVDS	10/100 Base-T MAC/phy. hardware, twisted pair	Ethernet 100 Base-T MAC/phy., twisted pair	Fibre Channel compatible transceiver over copper or fiber	1,000/10 G Base-T MAC/phy. hardware, twisted pair, or fiber
Topology (Tree, Point-to-point, Multi-drop, Daisy Chain)	Multidrop	Redundant multidrop	Multidrop and point-to-point (hub supports star)	Multidrop and point-to-point (hub supports star)	Multidrop	Cable—peer-to-peer with repeater (tree), noncyclic (1394b disables ports to break loops)	Point-to-point and switched	Generally spanning tree (hub), can be point-to-point and switched	Switched fabric	Point-to-point, arbitrated loop, tree (hub), switched fabric	10 G supports full-duplex (point-to-point or switched fabric only) 1 G also supports half-duplex (shared bandwidth using repeaters)
Supports Hot Swap of Same Type Nodes	Depends on implementation	Yes	Yes	Not specifically addressed	Yes	Yes, but swapping requires breaking network, depending on configuration	Yes	Yes	Yes	Yes, breaks loop in arbitrated loop topology	Yes
Supports Composability (Yes/No)	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Designed Specifically for Safety Critical Systems (Yes/No)	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No	No
Membership Service	No	No	Yes	No	No	No	No	No	No	No	No
Inherent Redundancy	Dual-redundant bus	Yes	Dual redundant bus, supports replica determinism	Yes for static frames on dual redundant bus, optional for other frames	No	No	No	No	Yes, dual redundant switches and links	No, but AE specified implementations are dual redundant	No
Redundancy Management	Defined at application level	Yes	Yes, inherently dual redundant, supports task and node replication (hardware/software)	No, must be implemented at application level	No	No	No	No	Defined at application level	No	No
Operate in Fault Tolerant (Fail-Op/Fail-Safe) Mode	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes, AE specified implementation	No

Table 1. Communication architecture comparison matrix (continued).

Feature	MIL–STD–1553	SAFEbus	TTP/C	FlexRay	TTCAN	IEEE–1394B	SpaceWire	Ethernet 10/100 Base-T	AFDX	Fibre Channel	Gigabit Ethernet
Fault Hypothesis	None published	Guaranteed to tolerate one arbitrary fault, may tolerate multiple faults At most, one component of any pair can fail	Guaranteed to tolerate one arbitrary fault Never give up strategy may allow tolerance to multiple faults for a given application	None published	None published	None published	None published	None published	None published	None published	None published
Fault Containment	Yes, if secondary bus can be used to remove or tolerate the fault	Yes, multiple levels of redundancy (pair-of-pairs for all components, fail silent nodes, shadow nodes)	Yes, in hardware, membership, message status, dual-redundant bus	No, FT must be implemented at the application level	Yes, if CAN controller is not faulty	No	No	No	Yes, if fault is confined to one dual-redundant switched network.	No	No
Babbling Idiot Avoidance	Not inherent, defined at application level	Yes, bus guardian	Yes, bus guardian	Uses timeout, no bus guardian	In the case of repeated faulty messages while CAN controller is not faulty, or if the application processor can place transceiver in stand-by	None	None	None	Detected and suppressed by switch	None	None
Message Failure Detection	Yes, status bit	Yes, BIU pairs check transmitted and received data	Yes, message status, global acknowledgement	Yes	Yes, by sender and receiver in hardware	No, in isochronous mode Yes, in asychronous mode (hardware)	Yes, parity, invalid destination, credit error, error end of packet	Yes, collision and RX at phy., no acknowledge (TCP, not UDP)	Yes, port detects overflow errors or switch identifies message failure and discards	Yes, link loss, acknowledgement, sequence error, message format	Yes TCP, not UDP
Tolerant to Message Loss	No, retransmit required	Yes, bus is quad redundant	On one channel	For redundant messages	No, retransmit only during arbitration phase	No, retransmit required	No	No, retransmit required	On one dual redundant switch network	No, retransmit required in standard config.	No, retransmit required
Prompt Communication Error Detection And Error Reporting	12 µs timeout for RT response (may be extended to >20 µs)	Yes, error detection is concurrent with message transmission/reception BIU reports error to host via registers	Yes (hardware), message error upon receipt, node fault within two TDMA communication cycles	Yes, message error during transmission and upon receipt	Yes (hardware), message error during transmission and upon receipt	Message receipt errors and acknowledge errors reported at link layer (hardware) Detection of presence of peer node at port	Link disconnect error reported in 1 µs	Collision detection (50-µs, hardware) and RX error at phy. Loss of communication between 2 nodes depends on network size—TCP, not UDP software	Variable, depending on link bandwidth and number of switches	Link errors and frame errors reported to sender through transmission of reject messages after error is detected Class 3 provides no acknowledgement Timing depends on network size and loads	Collision detection (50-µs, hardware) and RX error at phy. Loss of communication between 2 nodes depends on network size—TCP, not UDP software
Node Failure Detection (Controller Hardware Level)	Only for RTs, via response timeout, no other at hardware level	Yes	Yes	No	Yes	Via arbitration timeout or cable bias voltage loss	Only via link disconnect error and failure to reconnect Timeout indicator provided to application.	No	No	May be detected by missing acknowledge at link control facility	No
Node Failure Reported Consistently and With Low-Latency (Yes/No)	Only master knows	Yes, nodes fail silent; others detect by loss of scheduled communication	Yes, all functional nodes aware	No	To local application processor only	No	Yes, in the case of link failure only	No	Only nodes expecting data may be aware at application level	No	No
Tolerant to Node Loss	No, if bus master(s) is (are) lost, otherwise yes, communication still proceeds between remaining nodes	Yes, communication will proceed between remaining nodes	Yes, communication will proceed between remaining nodes	Yes, communication will proceed between remaining nodes	Can tolerate missing or unpowered nodes, but communication may not proceed correctly between remaining nodes in some cases	Depends on topology Only if an unused loop connection exists	Yes, communication will proceed between remaining nodes	Yes, communication can still proceed between remaining nodes	Yes, communication can still proceed between remaining nodes	Yes, communication can still proceed between remaining nodes	Yes, communication can still proceed between remaining nodes

Table 1. Communication architecture comparison matrix (continued).

Feature	MIL–STD–1553	SAFEbus	TTP/C	FlexRay	TTCAN	IEEE–1394B	SpaceWire	Ethernet 10/100 Base-T	AFDX	Fibre Channel	Gigabit Ethernet
Error Handling Approach	Terminal shutdown/ reset	Self-checking buses are used All BIU pairs check and compare all data traffic, BIU pairs must agree BIUs discard bad data and enforce fail silence	Replicated channels manage message loss on one channel; fail silence for protocol errors; FTUs (error masking); restart with self test	Message errors reported to host	Uses CAN message arbitration and fault management Node fails silent after transmitting max. number of error frames FT transceivers can communicate on one wire	Report error message codes from link layer Retransmit on loss of asychronous message	Link, parity, and credit error prompt reset of link and error reporting to application Reports detectable link physical connection faults to application	Retransmit on collision detection (MAC), loss of data (TCP, not UDP)	Switch can detect/ localize failures at the ports and discard bad messages No error/flow control on transmitted data Switch enters quiet mode for catastrophic failure	Retransmit on busy, reject, or lack of acknowledgement, request by recipient	Retransmit on collision detection (MAC), loss of data (TCP, not UDP)
Extensibility (Ease of Expansion)	Depends on implementation	Requires design of new schedule	Requires design of new schedule	Requires design of new schedule for new static slots	Requires design of new system matrix (message patterns)	Easy	Requires routing switch reconfiguration	Easy	Requires design of new switch configuration data table	Easy	Easy
COTS Test Equipment (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Availability of Off-the-Shelf Hardware (Yes/No)	Yes	No	Yes	Yes, consortium only	Yes	Yes	Yes	Yes	Yes	Yes	Yes
RAD-Hard/Tolerant Off the Shelf Parts	Yes	No	Yes, rad-tolerant via FPGA implementation	No	Yes, rad-tolerant via FPGA implementation	No, custom made exist	Yes	Somewhat, via rad-tolerant FPGAs (see FPGA IP entry below)	Somewhat, via rad-tolerant FPGAs (see FPGA IP entry below)	Yes (FC–1 and FC–2) via rad-tolerant FPGA. No rad-tolerant phy.	Somewhat, via rad-tolerant FPGAs (see FPGA IP entry below)
IP Available for ASIC Implementation (Yes/No)	Yes	Yes, but not necessarily to third parties	Yes	Yes, consortium only	Yes	Yes	Yes	Yes	Yes, limited availability	Yes	Yes
IP Available for FPGA Implementation (Yes/No)	Yes	Yes, but not necessarily to third parties	Yes	Yes, consortium only	Yes	Yes, link layer	Yes	Ethernet MAC	Ethernet MAC via FPGA implementation, no phy. AFDX specific functions are proprietary, limited availability	Yes (FC–1 and FC–2)	1/10G Ethernet MAC and PCS
Software Design Tools	Yes	Reported under development in 1992	Yes, system generation from high-level specs.	Yes, consortium only	Yes	No	No	No	Yes, application programming interface library	No	No
Open Specification	Yes	ARINC 659 is available for purchase by public SAFEBus spec. is proprietary	Yes, but implementation must be licensed	Yes, but implementation requires membership in or an agreement with the consortium	Yes	Yes, but implementation must be licensed	Yes	Yes	AFDX spec. is proprietary, ARINC 664 part 7 is available for purchase by the public	Yes	Yes
Formal Methods Applied	No	Details of assurance process not published	Yes	No	Yes	No	No	No	No	No	No
Notes	Bus must be tested to determine the effect of stubs/couplings	SafeBus is a registered trademark of Honeywell, and is currently the only implementation of ARINC 659		Consortium has expressed no interest in using FlexRay outside automotive applications	Availability of TTCAN level-2 hardware is limited at time of writing TTCAN can be implemented in software.		Space-rated hardware exists for SMCS (IEEE 1355 based) Most SpaceWire compliant hardware currently available as VHDL cores with the exception of router designs	Entries based on 10/100 Base-T using TCP or UDP	AFDX is a trademark of Airbus	Governed by multiple ANSI specifications (52 available from ANSI) Flexible and complicated	Entries based on 10/100 Base-X using TCP or UDP