

DEVELOPMENT AND EVALUATION OF AN ETHERNET-BASED NETWORK DEMONSTRATOR FOR CONTROLLING A NOVEL PASSENGER SERVICE UNIT IN THE AIRCRAFT CABIN

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Abstract

The network architecture of today's aircraft cabins is centralized and heterogeneous: proprietary bus systems, protocol converters and dedicated wiring add weight, complexity and power consumption. A consistently Ethernet-based, decentralized cabin network promises significant savings here. For connecting simple end devices deployed in large numbers, 10BASE-T1S as specified in IEEE 802.3cg is of particular interest, since this Single Pair Ethernet variant supports a multidrop bus topology. This paper investigates whether 10BASE-T1S is suitable for cabin applications. For that, a network demonstrator including eight nodes connected via a 25 m multidrop bus was built, representing the connection of several passenger service units (PSUs) to a higher-level control unit. A novel, display-based PSU serves as the example application. The demonstrator was evaluated with respect to goodput, robustness, modularity, audio playback synchrony and total cable length. The measurements resulted in a goodput close to the theoretical maximum, fair bandwidth distribution across seven simultaneously transmitting nodes and synchronization deviations below 1 μ s for multicast audio streaming. The sensitivity of the bus topology to disturbances on the trunk proved critical. 10BASE-T1S is therefore assessed as suitable for cabin functions of low design assurance levels (DAL).

Keywords

10BASE-T1S; Single Pair Ethernet; Aircraft Cabin Network; Network Demonstrator; Multidrop; Passenger Service Unit; PLCA.

1. INTRODUCTION AND MOTIVATION

The aviation industry is constantly trying to find ways to lower weight and power consumption of the aircraft. One area with considerable optimization potential is the internal network architecture of the aircraft cabin.

The network architecture and its components were developed in the 1980s and are characterized by a high degree of heterogeneity. For example, several communication protocols operate in parallel, increasing complexity and adding weight due to inefficient wiring and the required protocol converters. Migrating to a single, consistent communication technology such as Ethernet promises reduced network complexity, lower power consumption and weight savings. This supports Airbus' vision of a hyper-connected aircraft platform [1].

The research consortium DaKliF (Datenplattform für Klimaneutrales Fliegen – data platform for climate-neutral aviation, see Acknowledgements) investigates how a new ethernet based architecture can be implemented in the aircraft cabin. A particularly interesting technology for this purpose is 10BASE-T1S [2], a variant of *Single Pair Ethernet* (SPE) that requires only a single twisted pair and supports operation in *multidrop* mode. Multidrop architectures make it possible to avoid the additional switches that other topologies require. In addition, 10BASE-T1S provides an Ethernet-based alternative to the CAN bus currently used in aircraft cabins, enabling an “IP-everywhere” architecture without gateways [3]. Both arguments act directly on the component count and thus on mass and cost of the aircraft.

An obvious application for 10BASE-T1S in the cabin is the control of passenger service units (PSU). These are installed above the passenger seats and provide functions such as reading light control, playback of announcements, attendant call and the display of safety signs. Since PSUs are arranged linearly along the entire cabin, they notably benefit from a bus topology.

The main objective of this paper is to assess whether 10BASE-T1S in multidrop is suitable for applications in the aircraft cabin. To this end, a network demonstrator was built that connects eight nodes via a 25 m multidrop bus, representing the largest node count and bus length for which the standard guarantees operation (see 2.3). In the paper this network demonstrator reproduces the connection of several PSUs to a higher-level control unit. A display-based PSU developed as part of this work serves as the reference application from which the test scenarios are derived. The paper focuses on the network demonstrator and its evaluation with respect to goodput, referring to the throughput of useful data, as well as robustness, modularity, audio playback synchrony and total cable length.

2. STATE OF THE ART

2.1. Cabin network of current commercial aircraft

In modern Airbus aircraft, the cabin management system, called *Cabin Intercommunication Data System* (CIDS), is a highly centralized network [4]. A central management

server, the CIDS Director, controls the cabin equipment through distributed decoder/encoder units (DEU) [5]. For redundancy, two Directors are installed (three in the A380), one of which is active while the others operate in hot standby. Type A DEUs serve passenger functions – including the PSUs – and are connected via the proprietary *Top Line Bus* (Fig. 1) [6].

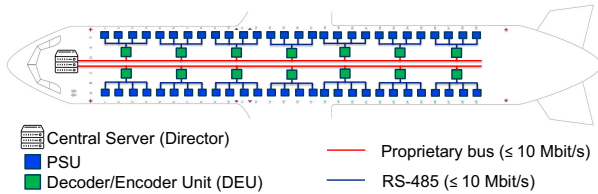


FIG 1: Simplified representation of the connection between the CIDS Director and the PSUs in Airbus aircraft (based on [7])

This architecture is functionally proven but exhibits structural drawbacks: multiple central computing units, several proprietary protocols requiring protocol converters, and limited data rates.

2.2. Decentralized Ethernet-based cabin architecture

The DaKliF consortium (see Acknowledgements) therefore pursues a decentralized, Ethernet-based cabin network as a potential successor to CIDS. The underlying idea is to combine different Ethernet variants according to bandwidth and latency requirements without changing the communication standard: fiber-optic Ethernet as the backbone, Gigabit Ethernet for bandwidth-intensive systems such as in-flight entertainment, *Time-Sensitive Networking* (TSN) for deterministic communication of safety-critical elements, and 10BASE-T1S for connecting less data-intensive components such as PSUs or lighting modules. Approaches to evaluating Ethernet-based cabin architectures can be found in [8] and [9], among others.

2.3. 10BASE-T1S according to IEEE 802.3cg

Classical Ethernet with switches and multi-pair cables is not optimal for embedded systems with many simple end devices: the mass of the wiring, the number of switches and the power consumption of high-speed PHYs are more critical here than in usual IT networks [10]. The IEEE 802.3cg task force [11] addressed this need and published the IEEE 802.3cg-2019 standard [2] in 2019, which defines two new physical layers: 10BASE-T1L for reaches up to 1000 m and 10BASE-T1S for short reaches. 10BASE-T1S transmits 10 Mbit/s in baseband over a single twisted pair. It supports either full-duplex operation in a point-to-point link or half-duplex operation in multidrop mode, in which the bandwidth of 10 Mbit/s is shared between all nodes on a common line. The standard guarantees reliable operation for at least eight nodes on a trunk of up to 25 m with stubs of at most 10 cm. A 100 Ω termination resistor is required at each end of the trunk in order to avoid signal reflections [2]. A vendor-independent SPE connector has not yet been established; the candidate form factors are defined in the IEC 63171-X series of

standards [12].

Without further configuration, 10BASE-T1S nodes on the bus use the classical CSMA/CD method for collision detection, identical to the original Ethernet over Coax. Optionally, *Physical Layer Collision Avoidance* (PLCA) can be enabled, a mechanism developed specifically for 10BASE-T1S that avoids collisions rather than detecting them and thus offers higher usable bandwidth and improved access latency under high network load [2].

2.4. Related work

Performance studies on 10BASE-T1S and PLCA have so far originated predominantly from the automotive domain. Min and Park investigate an interrupt-based extension of PLCA [13] and show that the latencies introduced by PLCA are still too high for time-critical applications, for which they propose node prioritization and packet segmentation [14]. Huszák considers backward-compatible enhancements for 10 Mbit/s SPE on shared media [10]. Gappa et al. model the crosstalk between a 10BASE-T1S bus and adjacent AC power wiring in an aircraft cabin use case closely comparable to the one considered here – eight nodes, 100 Ω terminations, stubs limited to 10 cm and AWG24 conductors – and conclude that crosstalk caused by power aggressors remains below the assumed limit, which supports the introduction of 10BASE-T1S in the aircraft domain [3]. An experimental assessment of network-level behavior – goodput, medium access under load, robustness against node failures – in a cabin-representative setup is addressed by this paper.

3. CONCEPT AND REQUIREMENTS

3.1. Network requirements

The network requirements were derived from a stakeholder analysis covering aircraft manufacturers, airlines, cabin crew, passengers and regulatory authorities. Ethernet is presupposed as the single communication standard, with IP-based communication between all nodes. The physical constraints of the bus follow directly from IEEE 802.3cg [2] (see 2.3). Tab. 1 lists the resulting requirements.

TAB 1. Requirements for the 10BASE-T1S network

ID	Requirement
RQ-1	PSU-coordinator communication: data transmission between several PSUs and a central processing unit (coordinator)
RQ-2	Bus topology: all nodes connected via a single linear bus
RQ-3	Robustness: continued operation with the remaining nodes if individual nodes fail
RQ-4	Modularity: straightforward modular extensibility
RQ-5	Total cable length: lower total cable length than a comparable network with standard Ethernet (RJ45, PtP)
RQ-6	Synchronous audio playback: multicast streaming of audio content to several end devices with a latency between devices imperceptible to the listener

In addition, regulatory requirements relevant to later certification were recorded: software development according to DO-178C depending on the *design assurance level*, environmental and interference qualification according to DO-160G, and cybersecurity according to DO-326A. Formal verification or certification is not within the scope of this work.

3.2. Concept of the network demonstrator

The demonstrator is intended to reproduce the part of the cabin network that connects several PSUs to a higher-level control unit. To place data transmission at the center of attention, it connects only the control units of the PSUs – without enclosures, displays or loudspeakers.

The physical setup deliberately realizes the limits for which IEEE 802.3cg guarantees operation: a linear bus topology (RQ-2) with eight nodes; a trunk of 25 m (the maximum reach specified) composed of 12.5 m between the coordinator and the first stub and 2.5 m between the subsequent stubs; stubs of 10 cm; termination resistors of 100 Ω at both ends of the bus; and an unshielded twisted copper pair as the medium (see 2.3). The measurements therefore characterize the worst case permitted under the standard, as buses that are shorter or carry fewer nodes can only perform better. For modularity (RQ-4), T-Adapters are provided for attaching additional nodes. Fig. 2 shows the resulting concept.

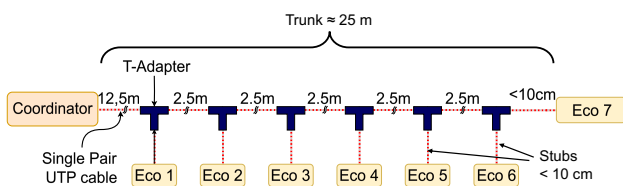


FIG 2: Concept of the 10BASE-T1S network demonstrator

3.3. PSU as example application

To provide a concrete use case for the evaluation, a novel PSU was developed as an example application. It replaces the mechanical buttons and indicators common today with three 2.8-inch touch displays, one per seat. The aim is to add numerous new features and to follow the ongoing trend of digitization in the cabin. Fig. 3 shows the front side of the developed PSU.



FIG 3: Developed Smart Passenger Service Unit

For the assessment of 10BASE-T1S, the PSU motivates the functional requirements: its touch displays require bidirectional communication with the coordinator (RQ-1), its arrangement along the cabin motivates the linear bus topology (RQ-2), and its loudspeaker requires the synchronous playback of announcements (RQ-6).

The developed PSU is controlled by the ZAL Endpoint Eco – a low-power edge-device developed at the ZAL.

4. IMPLEMENTATION

4.1. Nodes

The ZAL Endpoint Eco (Fig. 4) is the most energy-efficient member of the ZAL *Endpoints* developed at ZAL. It is based on an ultra-low-power Arm Cortex-M33 microcontroller STM32U575 and is equipped with a Microchip LAN8650/1 MAC-PHY Ethernet controller [15] for 10BASE-T1S. Connection to the cabin network is made through a 6-pin D369 connector qualified for aviation use [16], which carries both the 28 V supply typical of the cabin and the two SPE data lines. The coordinator for the demonstrator is a Linux-based controller with a USB-to-10BASE-T1S adapter (Microchip EVB-LAN8670-USB [17]).

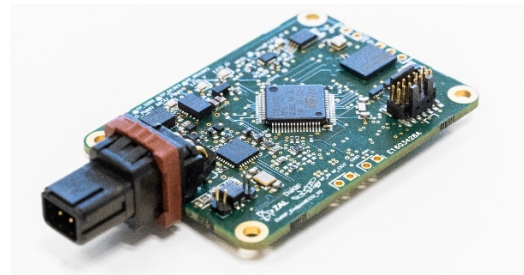


FIG 4: The ZAL Endpoint Eco

4.2. Wiring and connectors

The selection of connectors turned out to be one of the practical challenges. Since T-Adapters are not defined in the standard, the market offering is considerably smaller than for SPE connectors in general, and the survey identified a single manufacturer. T-Adapters and field-assembled connectors according to IEC 63171-2 from Rosenberger [18] were used.

The bus line is the unshielded aviation cable DRB24 [19] with two twisted 24 AWG conductors. One 12.5 m cable from the coordinator to the first T-Adapter, five 2.5 m cables between the T-Adapters and seven 10 cm stubs from the Ecos to the T-Adapters were assembled. The total length of the trunk is therefore about 25.1 m. Fig. 5 shows the assembled network demonstrator.

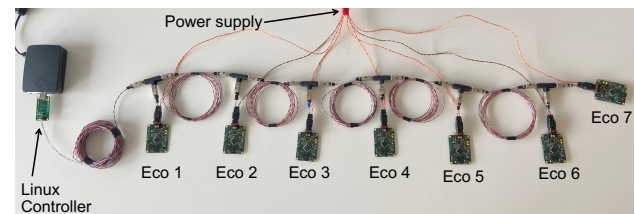


FIG 5: Assembled network demonstrator (10BASE-T1S bus) with eight connected nodes

4.3. Software

The Endpoint Ecos run Zephyr RTOS [20] version 4.2.0. The PLCA parameters and the MAC address are set through the network management interface of Zephyr. The

default values for the PLCA parameters of IEEE 802.3cg [2] (no burst transmission, TO timer = 32) are used. Each node receives a unique PLCA ID (0 for the coordinator, 1-7 for the Ecos), which is realized through a configuration parameter set at compile time.

The coordinator runs a DHCP server, an MQTT broker and the GStreamer multimedia framework [21], with which announcements are distributed to the nodes as an RTP audio stream over UDP multicast. For the goodput measurements, *iperf* [22] was used on the coordinator and *zperf* [23] on the Ecos.

5. EVALUATION

In order to answer the research question, the demonstrator was examined in five respects: goodput, robustness against disturbances, modularity, synchrony of audio playback and total cable length.

5.1. Goodput

Because of its low protocol overhead, UDP goodput was measured. Four scenarios were carried out, each with and without enabling PLCA: Eco → Coordinator, Coordinator → Eco, Eco → Eco, and seven Ecos simultaneously → Coordinator. The point-to-point measurements ran for 100 s. Since the start instant cannot be synchronized when several nodes transmit simultaneously, those tests were run for 500 s in order to minimize the advantage of the nodes starting first and last. Tab. 2 summarizes the results.

TAB 2. Measured UDP goodput in the 10BASE-T1S network

No.	PLCA	Client(s) → server	Duration (s)	Goodput (Mbit/s)	Packet loss (%)
1	no	Eco → Coord	100	9.54	0.01
2	no	Coord → Eco	100	9.55	0.1
3	no	Eco → Eco	100	9.55	0.01
4	no	7 Ecos → Coord	500	–	–
5	yes	Eco → Coord	100	9.42	0
6	yes	Coord → Eco	100	9.44	0
7	yes	Eco → Eco	100	9.44	0
8	yes	7 Ecos → Coord	500	$7 \cdot 1.36 = 9.52$	0

Without PLCA, a maximum goodput of 9.55 Mbit/s was achieved. That this value lies below 10 Mbit/s is to be expected: the 10 Mbit/s of the specification refers to the physical bit rate, whereas what is measured is the effective goodput. With the maximum Ethernet payload of 1500 bytes, IP and UDP headers (20 and 8 bytes) leave 1472 bytes of UDP payload. On the medium, each frame additionally carries the preamble and start frame delimiter (8 bytes), the MAC header (14 bytes) and the frame check sequence (4 bytes), resulting in 1526 bytes. Taking the interframe gap (IFG) of 12 bytes into account, the theoretical maximum goodput is

$$(1) \quad \frac{1472 \text{ bytes}}{1526 \text{ bytes} + 12 \text{ bytes}} \cdot 10 \text{ Mbit/s} = 9.57 \text{ Mbit/s}$$

The measured point-to-point values are therefore very close to the theoretical maximum. With PLCA enabled, the point-to-point rate drops slightly to between 9.42 and 9.44 Mbit/s, since the additional BEACON, COMMIT and SILENCE symbols consume bandwidth.

The benefit of PLCA becomes apparent under load. Without PLCA (test 4), one node blocked the bus continuously, so

that the remaining nodes could not transmit and no meaningful measurement was possible. With PLCA (test 8), the bandwidth was distributed evenly across the seven transmitters – 1.36 Mbit/s each, 9.52 Mbit/s in total – with entirely loss-free transmission. PLCA thus provides a fair distribution of bandwidth and prevents individual nodes from blocking the bus. It is notable that the aggregate rate under load exceeds the point-to-point values with PLCA: since all nodes use their transmit opportunities, most of the SILENCE phases are eliminated and the available bandwidth is utilized more effectively.

5.2. Robustness

To verify requirement RQ-3, throughput measurements were carried out during which a disturbance was introduced after 50 s. All tests ran for 100 s with PLCA enabled. Termination resistors were connected at the coordinator (PLCA ID 0) and at Eco 7. Tab. 3 shows the results.

TAB 3. Results of the robustness tests

No.	Client(s) → server	Disturbance	Effect
1	Coord → Eco 5	Physical disconnection of Eco 2 from the bus	No effect on the data rate
2	Coord → Eco 5	Physical disconnection of Eco 7 (carrying a termination resistor) from the bus	No further communication possible
3	Eco 1 → Eco 4	Loss of power at the coordinator	Increase of the data rate by 0.04 Mbit/s
4	Eco 2, Eco 5 → Eco 7	Loss of power at the coordinator	Data rate per Eco halved, approximately half of the packets lost

Disconnecting a node that is neither the coordinator nor carries a termination resistor (test 1) had no effect. When, in contrast, the node carrying the termination resistor at the end of the bus was disconnected (test 2), the resulting reflections caused a complete loss of communication. Eye diagrams recorded with an oscilloscope confirm the drastic degradation of signal quality in the absence of termination. This is, however, a known drawback of the bus topology in general [24] and not specific to 10BASE-T1S. In the demonstrator, the termination resistor was located in the end node itself. Placing the terminations independently of the attached devices would prevent this failure mode. Damage to the trunk itself, such as a cable break, would still affect all nodes.

The failure of the coordinator shows the fallback behavior described in the standard. With a single transmitter (test 3), the PLCA overhead is eliminated, and the data rate increases marginally. If, on the other hand, two nodes transmit simultaneously (test 4), the network falls back to CSMA/CD, collisions occur and the data rate per node is halved with substantial packet loss. The coordinator is thus not a single point of failure for connectivity, but it is one for the performance of the network under load.

5.3. Modularity

In a hot-plug test, additional Ecos were inserted into the running bus via T-Adapters without powering off the existing nodes. The new nodes were able to communicate in the network within a few seconds. The network can therefore be extended without additional hardware or software configuration, as long as T-Adapters are used.

5.4. Synchrony of audio playback

Cabin announcements must be reproduced at all PSUs with sufficiently low synchronization error so that no echo effect is perceptible. For this measurement, the audio application was modified to toggle a GPIO at the start of playback. This application was running on all seven Endpoint Ecos while a multicast stream was started. The GPIO signals of the nodes at the beginning, in the middle and at the end of the bus were recorded with an oscilloscope (Fig. 6) and the maximum deviation was documented over 100 runs.

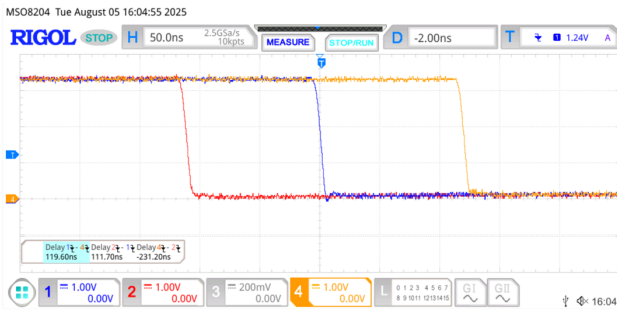


FIG 6: Oscilloscope recording of the GPIO signals at the start of audio playback. Distance from the coordinator: channel 1: 12.5 m, channel 2: 20 m, channel 4: 25 m.

The mean deviation was 225 ns and the maximum 553 ns. Both values lie below 1 μ s and thus about five orders of magnitude below the echo threshold of approximately 50 ms [25]. A supplementary listening test with two Ecos connected to loudspeakers confirmed this: no echo effect was perceptible. The evaluation shows that announcements can be distributed via 10BASE-T1S using UDP multicast without the need for additional synchronization mechanisms.

5.5. Total cable length

The main structural advantage of the multidrop topology lies in the wiring, as other Ethernet variants would require point-to-point links (star topology). For comparison, the total cable length was calculated analytically for both topologies using an arrangement representative of an actual cabin installation (Fig. 7): seven PSUs mounted above consecutive seat rows of an A320-class aircraft, spaced at the typical economy-class seat pitch of 32 inches (0.81 m), rounded to 0.8 m [26], under the assumption that all nodes have to be connected to a coordinator, located at the center.

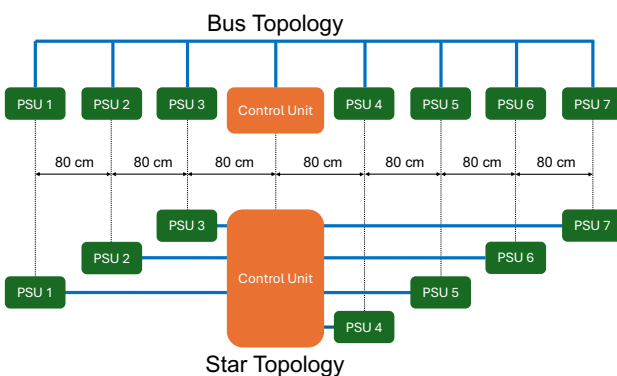


FIG 7: Wiring for a linear node arrangement: bus topology (top) and star topology (bottom)

For the bus topology, the total length is composed of the trunk spanning the eight nodes ($7 \cdot 0.8 \text{ m} = 5.6 \text{ m}$) and the eight stubs of 10 cm, and amounts to 6.4 m. The star topology requires a dedicated line from the coordinator to every node and thus reaches 12.8 m, corresponding to a factor of 2. Furthermore, the bus topology requires fewer connectors and occupies only a single port at the coordinator, whereas the star topology needs one dedicated port per node. To assess the actual weight saving, however, the mass of the cables and connectors as well as the specific arrangement of the end devices must be taken into account. Considering length alone yields only an upper bound on the potential.

6. CONCLUSION AND OUTLOOK

The network demonstrator built in this work demonstrated stable 10BASE-T1S communication across eight nodes and a 25 m multidrop bus. At 9.55 Mbit/s, the goodput almost reaches the theoretical maximum; PLCA distributes the bandwidth fairly and without loss across all transmitters under load; the network can be extended by further nodes during operation; and announcements are reproduced practically synchronously, with deviations below 1 μ s. For the arrangement considered, the total cable length is lower than that of a star topology by a factor of 2.

At the same time, the results reveal clear limitations. The bus topology is sensitive to disturbances on the trunk: the loss of a termination resistor led to a complete loss of communication. For deployment in an aircraft, additional measures are required to mitigate the effects of disturbances. The limitation to eight nodes per bus is a substantial limiting factor, since connecting all PSUs of an aircraft would require additional switches. For time-critical functions, PLCA in its present form introduces latencies that are too high [14]. A further technology for additional weight savings, which is not supported for 10BASE-T1S in multidrop mode, is Power over Data Lines (PoDL). PoDL allows supply and data to be carried over the same twisted pair, so that only two instead of four conductors need to be routed along the cabin. For 10BASE-T1S, PoDL is officially specified only for point-to-point operation, although successful implementations for multidrop exist [27].

Several developments address these points. First 10BASE-T1S PHYs with TSN support are available [28], and extensions to PLCA such as node prioritization and packet segmentation have been proposed [14]. The 10BASE-T1M specification of the IEEE 802.3da project supports at least 16 nodes, a reach of 50 m and PoDL, and was published in March 2026 [29]. Multidrop SPE is therefore likely to become increasingly attractive for aviation.

With respect to the research question, it can be concluded: **for cabin functions of low DAL, 10BASE-T1S in multidrop mode is suitable**, especially where many simple end devices are distributed linearly along the cabin. Prior to integration into an actual aircraft, the regulatory aspects must additionally be addressed – in particular the demonstration of immunity to environmental influences according to DO-160G and software development according to DO-178C in line with the applicable design assurance level. Further work should investigate the new 10BASE-T1M variant with PoDL, the operation of several coupled multidrop segments via switches, the design of redundant bus lines, and the combination of multidrop Ethernet with TSN in the cabin context.

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