Performance evaluation of deterministic communication in the railway domain

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***Abstract*—This paper presents an in-depth physical evaluation that studies the inclusion of deterministic and mixed-criticality features on the train communication networks. Currently, the railway industry uses networks with multiple backbones. The most prominent are communication setups with the WTB/MVB(Wire train bus/ multifunctional vehicle bus) and the ETB/ECN (Ethernet Train Backbone/ Ethernet Consist network). Where the WTB/MVB is used to host safety-criticality applications, the ETB/ECN is used for non-safety criticality applications, since the ETB/ECN is not able to provide determinism. Nevertheless, the main reason for the addition of the Ethernet-based communication is the high bandwidth availability, to satisfy the increasing data traffic generated by applications on the train. However, these mixed networks create greater complexity, increased cable length, weight and maintenance cost as a result of two different topologies. This paper proposes and evaluates TTEthernet as means to provide determinism and mixed criticality platform for the train communication network (TCN). A fault injection approach is adopted for the evaluation, and the performances of ETB/ECN profile and TTEthernet are observed under a babbling idiot failure mode. The ETB/ECN profile is used as a baseline to reveal specifically the rate-constrained (RC) traffic type behaviour of TTEThernet.**

***Index Terms*—Fault Injection. Deterministic communication. Train communication network. TTEthernet. Performance evaluation. Mixed-criticality. Virtual links.**

I. INTRODUCTION

The current electronic systems found in trains consists of applications running at different safety-criticality levels. Such applications include propulsion control, door controls, diagnostics, seat reservations, and so on. These applications host multiple embedded devices situated in a distributed manner in the train vehicles. A real-time communication system is necessary to ensure efficient communication between these embedded devices, hence the development of the Train Communication Network (TCN) standard [1], which provides the guideline for exchanging information between devices on railway vehicles. The establishment of a common standard for the electronic coupling of the vehicle's electronic equipment was the motivating factor behind the TCN development [2]. Before the development of this standard, the railway communication system was mostly proprietary solution, and tailored to meet specific requirements of railway operators and vendors.

TCN functions on a hierarchical model consisting of two network buses, the Wire Train Bus (WTB) and the Multi-function vehicle bus (MVB). The initial version of the TCN standard (IEC 61375-1, IEC 61375-2-1ff) did not take care of applications having large bandwidth, such as surveillance cameras and onboard entertainment. The data rate of this earlier TCN version tops at 1 Mbit/s between the train vehicle (Train bus) and 1.5Mbit/s within a vehicle (Vehicle bus). Therefore, this resulted in the development of additional parts to the IEC 61375-family. The improved standard defined a faster TCN (IEC61375-2-5) capable of handling over 100 Mbits/s, and conformant to IEEE 802.3. This standard is referred herein as the ETB/ECN and is based on a hierarchical model, comprising the Ethernet Train Backbone (ETB) and the Ethernet consist network (ECN).

However, the railway industry still uses the WTB/MVB for safety functions, such as traction control, brakes, and doors. While the ETB/ECN bus is used for high bandwidth functions such as for passenger's comfort (entertainment) and passenger information (e.g. audio message) [3], this presents a mixed network with two backbones, one for ETB/ECN and the other WTB/MVB. Apart from the increase in complexity brought by this solution, there is an extended cable length and an increase in maintenance cost resulting from two different network topologies. Recently, a European railway project titled "SAFE4RAIL" [4] began to address these problems. SAFE4RAIL proposed the use of a deterministic platform for the train communication network. The determinism and bounded jitter feature of certain networks termed "deterministic" provides a way to support mixed criticality traffic. It is expected that future communication system in the railway industry will utilise this mixed criticality feature of deterministic networks to reduce wiring/weight, complexity, and maintenance cost. Deterministic platforms such as TSN [5] and TTEthernet [6] were considered during the SAFE4RAIL project. This is due to the anticipated worldwide acceptance, integrability and its cost-effectiveness, which are critical considerations for the railway vendors. The proposed integrated modular platform for the train control and management system (TCMS) in SAFE4RAIL was based on such a deterministic communication platform.

In this work, we evaluate the application performance of TCN-TTEThernet (TCN based on a TTEthernet profile). The results of the evaluation herein provide a means to compare

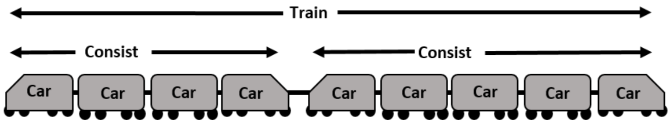

Fig. 1. Train composition

the performance of TTEthernet to other deterministic and non-deterministic platforms quantitatively. Our work evaluates the application behaviour in the presence of network faults, to aid the implementation of adequate fault coverage. Under a network flooding failure scenario, we observe both TCN-ETB/ECN (TCN based on ETB/ECN profile) and TCN-TTEthernet. To the best of our knowledge, this is the first performance evaluation that uses a fault injection approach for TCN-TTEthernet. The fault injection framework used was designed in [7], and is capable of injecting, observing, and analysing various network faults such as corruption, omissions and network flooding. The fault injection framework provides the platform to evaluate the actual hardware behaviour in the presence of faults as opposed to evaluation using models provided in mathematical or formal methods. For this reason, fault injection is used to evaluate the performance of the implemented train communication system. The framework can thus be used, to test hardware implementation of TCN based on several deterministic platforms, to ensure conformance to standards, and to verify proper functionality.

Our work, therefore, provides the following contributions.

- Provides the baseline for future comparison of TCN-TTEThernet to other deteministic networks.
- Exposes the impact of failure scenarios on the safety and performance of applications over TCN.
- Proposes and illustrates the use of fault injection framework for performance evaluation of TCN.
- Exposes the efficacy of TTEthernet as a suitable underlying network for TCN, specifically at layer 2 of the OSI stack.

The terminologies used to describe the train system in this work are illustrated in Figure 1. The *car* is the smallest unit from the physical composition. However, from a network perspective, multiple *cars* can constitute a *consist*. A train fleet is made up of multiple *consists*.

The rest of this paper is structured as follows. Section two discusses the related works. Section three gives an overview of TCN, TTEthernet and fault assumptions. Section four presents the TCN use-case description. The experimental set-up is described in section five. The results and discussions are presented in section six. Section seven concludes the work.

II. Related works

Performance evaluation on the TCN was earlier carried out in [8]. The authors adopted a simulation approach to evaluate the real-time performance of the WTB/MVB communication system of the Korean High-Speed Train (KHST). The evaluation in [8] was done for the network medium allocation scheme and the medium access control algorithm. However, despite the importance of this evaluation, the target network (WTB/MVB) is foreseen to be replaced in modern trains, primarily because of its low bandwidth availability. In addition, the work used a simulation-based approach as opposed to a physical hardware setup for the train communication system, in contrast to the strategy adopted in our work. The work in [8] did not also consider the performance evaluation under faulty scenarios, which is valuable in ascertaining the robustness of the network.

The propulsion control system in trains over Ethernet was evaluated in [9]. The work supports the view that the legacy Ethernet-based standard is not able to guarantee the fixed and sustained data rate required for safety criticality functions such as propulsion control and braking controls, this was a key motivation for studying the performance of the propulsion control over Ethernet. The work in [9] employed co-simulation using a MATLAB/SIMULINK based toolbox; the TrueTime Toolbox. Although the view that acknowledges the insufficiency of legacy Ethernet for safety criticality functions aligns with ours, nevertheless we propose the use of a deterministic Ethernet (TTEthernet). Furthermore, the work in [9] did not consider performance evaluation under failure scenarios.

Additionally, more works on performance evaluation carried out for train communication include [10] for train communication system using radio network and [11] for mmWave in 5G Train communications. However, performance evaluation under failure scenarios was not within the scope of these works.

III. Overview of TCN and the TTEthernet

A. Overview of TCN

A comprehensive description of TCN based on WTB and MVB (TCN-WTB/MVB) is giving in [1] and [2]. TCN comprises the train bus that connects vehicles and the vehicle bus that connects the pieces of equipment within the vehicle. The former is referred to as the WTB and the latter the MVB. The WTB uses either jumper cables or automatic couplers to interconnect vehicles. The twisted shielded-wire is the preferred media for message transmission, because of its reliability feature in the railway use-case [2]. The WTB can function at a length up to 860 meters and is capable of carrying data at 1 Mbps. WTB transmits data using the Manchester encoding scheme. One of the essential features of WTB is the ability to number its nodes (vehicles) sequentially and also determine the train topography and node's orientation relative to each other. This operation is called inauguration. The MVB can operate over optical fibres (distances over 200m), 120-ohm twisted wire pairs (reaches up to 200m) and RS-485/120-ohm cable to realise low-cost solutions. The MVB operates at 1.5 Mbps over these media.

Three types of data are transmitted over TCN-WTB/MVB namely, *process variables*, message data (*messages*) and *supervisory data* [8]. Critical messages such as the commands issued by the train operator and the train's state are the contents of the *process message*. TCN-WTB/MVB specifies two delay requirements for *process message*, a delay less than 100 ms at WTB level (two consecutive vehicles), and a delay less than 50 ms for traction control at MVB level [8]. *Process messages* require very short delays and determinism. Non-critical messages such as passenger information are transmitted through the contents of the *message* traffic. The message length is longer compared to the *process messages*. The delay tolerance is relaxed for the *message* traffic. The *supervisory data* are management frames used to check the status of the devices. It is used to detect silent devices, inauguration, and other supervisory functions. The *supervisory data* and *message* data exhibit the same transmission pattern. Therefore, the *supervisory data* can thus be handled as part of *message* data.

TCN-WTB/MVB provides periodic and sporadic medium access. The periodic access is used for the *process message* traffic, while the sporadic access is used for the *message* traffic. TCN-WTB/MVB assigns a *master* role to a device that controls the granting of access to the medium. After the transmission of *process variables*, the master performs a check to determine if there is enough time to send a sporadic message (i.e. *messages* traffic) before the next allocated period. The first master frame is needed to synchronize all clocks with jitter in the microseconds range [2].

Train communication networks based on Ethernet Train Backbone (ETB) and Ethernet Consist Network (ECN) is briefly discussed in [12]. The ETB/ECN technology is adopted for *train-level* and *consist-level* communication. The ETB/ECN is a new generation TCN, and it also adopts a hierarchical architecture as the WTB/MVB. The standards IEC 62580-2, IEC 61375-2-4, (application profile), IEC 61375-2-3 (Communication profile), IEC 61375-2-5 (Train Backbone Network) and IEC 61375-3-4 (Ethernet Consist Network) specify the various layers of the ETB/ECN. In comparison to the WTB/MVB, ETB/ECN provides support for onboard multimedia data, which includes surveillance/CCTV [12]. An ETB/ECN network has higher bandwidth of 100 Mbps, and its data packet size is up to 1500 bytes. The higher bandwidth provides the capacity to transmit video surveillance, process, maintenance, status monitoring, and diagnostic data. ETB can provide up to 200 Mbps bandwidth with link aggregation [12]. The ETB/ECN adopts VLAN (Virtual Local Area Network), multicast, QoS, and redundancy management to ensure real-time, reliability, and safety of the TCN.

B. Overview of TTEthernet

The TTEthernet is a deterministic layer 2 protocol, standardized as SAE AS6802 [6]. TTEthernet is a real-time communication protocol that is compatible with standard Ethernet and provides additional services for a distributed real-time system [13]. TTEthernet introduced an IEEE802.3 compatible implementation that guarantees determinism for critical applications. It provides the platform to host network traffic of different criticality on the same link. TTEthernet provides temporal and spatial partitioning for the messages in the network. This partitioning promotes the use of TTEthernet for mixed-criticality applications. Therefore, both safety and non-safety criticality applications can be deployed in a way that reduces cost (e.g. wiring), size, weight and power and yet still guarantees reliability. TTEthernet structures its traffic classes into three types namely, Time triggered (TT), Rate-constrained (RC) and Best effort (BE) traffic. An outstanding feature of the TTEthernet is the fault tolerant synchronization service that ensures that all the network participants are synchronized. Using this synchronization service, TTEthernet satisfies very tight timing constraints (tight latency and minimal jitter). A detailed description of TTEthernet services and operational principle can be found in [14].

C. Fault Assumption

TTEtherent provides a means to configure the end nodes and switches with high integrity. The high-integrity design uses a commander/monitor (COM/MON) system to realize a fail-silent node [14]. It is assumed that any message sent by a fail-silent node can only be a correct message. If we consider a TTEtherent switch in line with this assumption, it will certainly forward only the correct messages. In the case of an end system, which is the origin and sink of the message, failures can occur before it is fed into the COM/MON. The COM/MON only aims for error-containment that occurs within a device.

According to the IEC 61508 standard [15], communication failure measures are to be estimated to take into account failure modes such as transmission errors, repetition, deletion, corruption and delay. In this work, we use the babbling idiot failure for our evaluation, which assumes a repetitive failure profile. The babbling idiot (referred afterwards in this work as network flooding) is characterised by the transmission of arbitrary messages at random points in time. A faulty node that monopolises the shared channel by sending messages at erroneous points in time is perceived to have a babbling idiot failure [16]. The babbling idiot failure can originate either from the end system hardware or software. A hardware babbling idiot occurs when the failure is caused by the direct consequence of a hardware fault. A software babbling-idiot describes when the error originates from the application software (e.g. a bug in the code or human factor such as a malicious attack). The TTEthernet uses a traffic policing mechanism and a central guardian system to protect against babbling idiot failures. However, we evaluate the implication of these mechanisms when hosting railway applications.

IV. TCN USE-CASE DESCRIPTION

The communication infrastructure in the railway systems consists of multiple end devices (ECUs) that perform several operations, as illustrated in Figure 2. An ECN forms a unit that connects applications within a car. Although not captured in Figure 2, an ECN can consist of multiple cars that form a consist network. However, the diagram illustrates the hierarchical architecture of TCN, which is made up of the ETB and ECN network. The ETB connects multiple ECNs. The operator's cabin is positioned at the leading consist. The applications captured in the use-case have different levels of

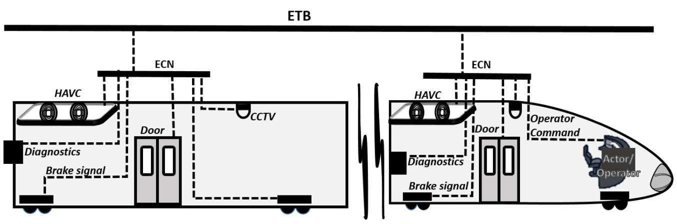

Fig. 2. Train Consist network

safety criticality classification. The applications considered include the following.

- Surveillance: The CCTV (closed-circuit television) cameras. This application has a high bandwidth requirement.
- The train braking system, considered in this work as safety-critical, with a higher priority than the surveillance system.
- Heating, Ventilation and Air Conditioning (HVAC) are considered in this work as safety critical.
- Diagnostic services, in this use case, are provided by each consist. The results are accumulated in the operator's cabin.
- Door Control: The use case includes ECUs (Electronic control units) for doors that are controlled by the operator's cabin.

Our work evaluates the performance of these applications when hosted on the same network. We observe the added value of the temporal and spatial partitioning of the different application message provided by TTEthernet. The current TCN-ETB/ECN was used as a baseline to understand the improvements given by TTEthernet.

V. Experimental Setup

The analysis of a train topology comprising four *consist* networks connected via a redundant ETB line is carried out. Firstly, we set up a communication network between the *consists* using the existing TCN-ETB/ECN profile. Figure 3 shows the connections between the four *consists* network. The ETBN is a setup of switches implemented in an FPGA based board; NetLeap Base Board by novtech. The ECNs are also implemented on the Netleap boards to exchange traffic between each other. Traffic traverses the ECN nodes via redundant channels. The VLANs map to two different categories of network traffic, to provide the partitioning required for the different message types. Table I illustrates these mappings.

The VLANs are configured on different broadcast domains. Based on the IEEE 802.1Q, priorities were allotted as follows — priority level 7 for break and door control, and priority level 5 for all others. The column *message directon* illustrates the direction of messages on the ETBN channel. For instance, on VLAN1, the network ECN_4 transmits HVAC control commands to ECN_1, ECN_2, and ECN_3.

Secondly, a similar profile was further set up for TTEthernet. One major difference is the replacement of VLANs with Virtual Links. Virtual links are used to partition the different applications running on the network. A virtual link is of ARINC 664-part 7 [17] origin and it is integrated as a part in the TTEthernet standard. The virtual link establishes a static path between one transmitter and one or several receivers. It specifies a logical communication path between one source application to one or more destination applications (*situtated in one or multiple nodes*). Table II illustrates the senders and receivers assigned following the virtual link concept. The TTE-Switch A664 Lab switches and end-systems by TTTECH were used for the ETBNs and ECNs, respectively. The four ECN nodes exchange messages between each other using these virtual links. The safety (e.g. Brakes), non-safety criticality (e.g. Diagnostics) messages and applications that require high QoS (e.g. CCTV) are assigned different virtual links. The assignments are based on the level of criticality. In TTEthernet, three message classes (TT, RC and BE) can be assigned to provide temporal and spatial partitioning of the messages exchanged between these applications. The setup demonstrates how rolling stock applications that have mixed criticality levels could be hosted on the same network infrastructure and yet share a common link. Safety critical applications such as the brake and door control were assigned higher priorities than lower criticality applications such as diagnostics and CCTV.

To observe the performance of TCN-ETB/ECN and TCN-TTEthernet under failure, ECN_1 was conditioned to fail in a manner to flood the network. The flooding was generated by a babbling-idiot failure mode implemented in an FPGA and connected on link L1 and L2 in Figure 3. To obtain the end-to-end latencies, measurement probes were placed on both ports of ECN_2, ECN_3, and ECN_4. The entire network traffic was monitored using network accelerator cards (*NT4E2-4-PTP by Napatech*).

TABLE I
VLAN profile for TCN based on ETB/ECN

VLAN Name	Message Direction	Application map
VLAN1	ECN_4 → ECN_1,ECN_2,ECN_3	HVAC control
VLAN2	ECN_4 → ECN_1,ECN_2,ECN_3	Brake control
VLAN3	ECN_4 → ECN_1,ECN_2,ECN_3	Door control
VLAN4	ECN_1 → ECN_4	CCTV
VLAN5	ECN_2 → ECN_4	CCTV
VLAN6	ECN_3 → ECN_4	CCTV
VLAN7	ECN_3 → ECN_4	Diagnostic

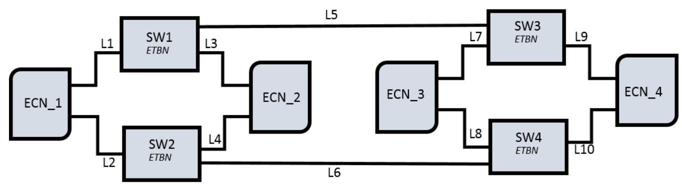

Fig. 3. Train network setup based on TTEthernet

TABLE II
VIRTUAL LINK PROFILE FOR TTETHERNET USE-CASE FOR RAILWAY

VL Name	VL Direction	Application map
VL1	ECN_4 → ECN_1,ECN_2,ECN_3	HVAC Conrol
VL2	ECN_4 → ECN_1,ECN_2,ECN_3	Brake Control
VL3	ECN_4 → ECN_1,ECN_2,ECN_3	Door control
VL4	ECN_1 → ECN_4	CCTV
VL5	ECN_2 → ECN_4	CCTV
VL6	ECN_3 → ECN_4	CCTV
VL7	ECN_3 → ECN_4	Diagnostics

VI. RESULTS AND DISCUSSION

A C++ software is used to analyse the results obtained; to obtain the latency of individual VLANs/VLs, jitter and number of dropped packets. This work first investigated a *golden run* scenario, before running an investigation under the given failure scenario. A *golden run* is an experiment without any faults injected. It is used to obtain a baseline to compare and determine the effect of faults when injected.

A. Behavior of TCN-ETB/ECN

Table III shows the results obtained from a *golden run* experiment and an experiment under the network flooding scenario. The measurements are taken for the ECNs that were not conditioned to fail; ECN_2, ECN_3 and ECN_4. It can be observed from Table III that the average latency is reflected in the number of hops and distance between the ECNs as expected. In the *golden run* scenario, the average latency value of VLAN1(ECN4 - ECN2), VLAN2(ECN4 - ECN2) and VLAN3(ECN4 - ECN2) is 179.8 μs, while all VLANs from ECN4 to ECN3 is approximately 89.8μs.

Figure 4 illustrates the impact of network flooding on the average latency. The VLANs herein are assigned a VLAN map number to indicate the direction and participants (ECNs involved). For example, the map represented with the number ***1***, is used to represent VLAN1(ECN4 - ECN2) in Figure 4. It can be observed that VLAN5, VLAN6 and VLAN7, corresponds with VLAN mapping 7-9 respectively on the figure, and it is affected by the failure of ECN_1 (*VLAN4*). The affected VLANs on the Ethernet full-duplex communication are on the traffic sent on the same direction with the network flooding. The average latency is increased due to the shared egress access to the switches.

The sporadic generated messages emulated from ECN_1 has an impact on all ETBNs. Thereby, the average latency of VLAN5(ECN2 - ECN4), VLAN6(ECN3 - ECN4) and VLAN7(ECN3 - ECN4) is increased by 30.4μs, 58.7μs and 35.72μs respectively. In this work, the transmission selection algorithm used is the strict priority. VLAN4 shares the same egress resource with VLAN5 on SW1 and SW2. It also shares the same egress resource with VLAN6 and VLAN7 on SW3 and SW4. The effect of networking flooding, therefore, increases the average latency on the affected VLANs and results in a significant jitter increase.

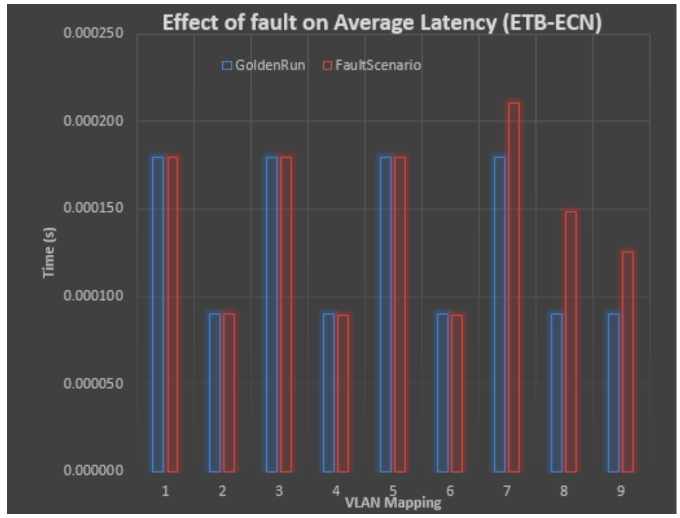

Fig. 4. Effect of fault on Average Latency for TCN-ETB/ECN

The effect of the failure on jitter is shown in Figure 5. Similar to the average latency, it can be seen that the VLAN5(ECN2 - ECN4), VLAN6(ECN3 - ECN4), and VLAN7(ECN3 - ECN4) are profoundly affected, with a jitter increase of 78μs, 167μs, and 162.2μs respectively.

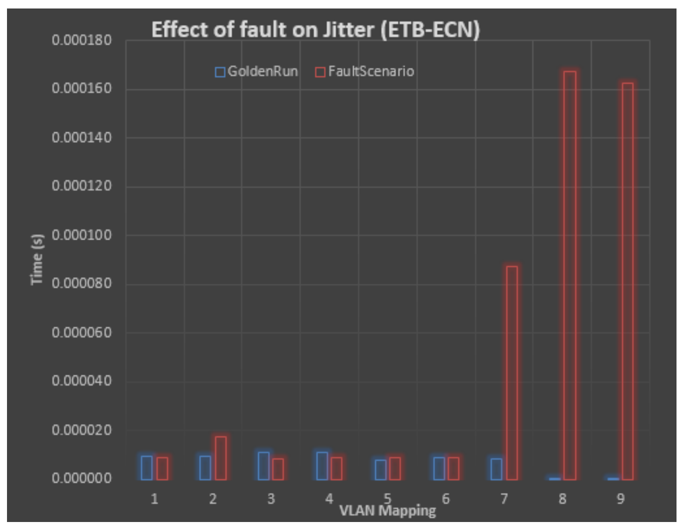

Fig. 5. Effect of fault on Jitter for TCN-ETB/ECN

B. Behaviour of TCN-TTEthernet

The train use case in this work observed RC behaviour on TTEthernet. TT behaviour is minimally affected by the network flooding, as every VL is assigned a time slot that provides temporal isolation. TT traffic can only be delayed for a maximum of one message length, when *shuffling* [14] is used for conflict resolution. The TT delay inflicted by shuffling is due to the concept of not having fragmented packets, so lower priority traffic is allowed to finish transmission even if the time slot allocated to TT traffic is reached. However, it remains a

TABLE III
EXPERIMENT RESULTS FOR TCN-ETB/ECN

VLAN[map]	GR-Avg Latency (µs)	Failure-AvgLatency (µs)	GR-Jitter (µs)	Failure-Jitter (µs)
VLAN1(ECN4 - ECN2)[1]	179.8568	179.6034	9.2200	8.7700
VLAN1(ECN4 - ECN3)[2]	89.8794	89.6724	9.2900	17.4000
VLAN2(ECN4 - ECN2)[3]	179.8549	179.6263	11.0100	8.1700
VLAN2(ECN4 - ECN3)[4]	89.8779	89.5754	10.8200	8.6900
VLAN3(ECN4 - ECN2)[5]	179.8529	179.5749	7.6500	8.7100
VLAN3(ECN4 - ECN3)[6]	89.8832	89.6052	9.1800	8.6600
VLAN5(ECN2 - ECN4)[7]	179.8053	210.2321	8.5900	87.5600
VLAN6(ECN3 - ECN4)[8]	89.8675	148.5840	0.3400	167.4300
VLAN7(ECN3 - ECN4)[9]	89.8684	125.5891	0.3400	162.5200

design decision whether to halt transmission of low priority traffic on arrival of TT traffic.

Table IV shows the results obtained with an underlying TTEthernet platform. The first column represents the virtual link members and the direction of traffic. The rest of the column headers have similar explanations to Table III. In the case of TTEthernet, only one virtual link is affected; VL5(ECN2 - ECN4)[7]. VL5 is in the same direction as VL4 and share common ETBN switches (SW1 and SW2). Since VL4 and VL5 are both RC messages, the sporadic generation of VL4 messages affects VL5, but not beyond the redundant ETBN switch-pair SW1 and SW2. Although VL6 and VL7 are in the same direction and share the same egress port on SW3 and SW4, they remain unaffected by the failure due to the frame filtering and policing performed by AFDX compliant switches (ARINC 664 switches).

Figure 6 further illustrates the impact of the failure on the average latency of VL5 (VL mapping representation on chart no. 7). The average latency is increased by 27 ms. Figure 7 shows the effect of failure on Jitter. Similar to its average latency, only VL5 is significantly affected. The jitter value is increased considerably by 5 ms as RC messages Queue at the egress of SW1 and SW2. The network failure injected via VL4 creates contention on the shared resource (egress port of SW1 and SW2). ARINC 664-Part 7 defines two priorities for virtual links: *high* or *low*. In this work, the priority of VL4 and VL5 is set to *high*. Unlike TT traffic, the RC traffic does not share any notion of global time and are not synchronised to the other network participants (network switches and end systems). Therefore, frames from VL4 and VL5 that ingresses SW1 and SW2, and then egresses via the same output port compete. The data contention issue between VL4 and VL5 (RC messages) are addressed through buffering, which is a technique specified by ARINC 664-Part 7. It is then in the part of designers to ensure that delays imposed by the frames (even in such a network flooding failure mode) is lower than the accepted delay for a given virtual link and that there is no frame loss as a result of buffer overflow. A detailed study on delay encountered by frame traversing an ARINC 664-Part 7 compliant switch and the techniques used to ascertain the worst-case delays can be found in [18]. However, our work further pushes the need for critical consideration of failure cases, and its impact on the worst-case delay.

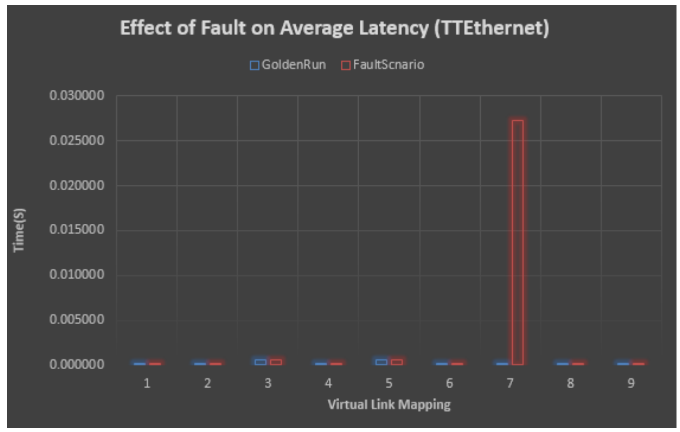

Fig. 6. Effect of fault on Average Latency for TCN-TTEthernet

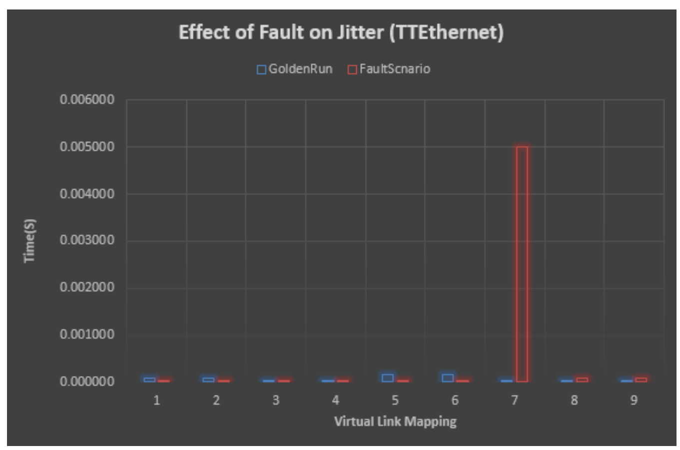

Fig. 7. Effect of fault on Jitter for TCN-TTEthernet

VII. CONCLUSION

In this work, we analysed the impact of failure on TCN for mixed-criticality applications. We explored the feasibility of TTEtherent as the underlying platform for TCN and evaluated its behaviour under the presence of network failure. We utilised a fault injection approach that uses a framework, in which a network flooding failure was triggered, and the effect on the performance of TCN based on ETB/ECN, and TCN based on TTEthernet is evaluated. In the case of TTEthernet, only the latency and jitter of RC virtual link which shares the

TABLE IV
EXPERIMENT RESULTS FOR TCN-TTETHERNET

VL[map]	GR-Avg Latency (µs)	Failure-AvgLatency (µs)	GR-Jitter (µs)	Failure-Jitter (µs)
VL1(ECN4 - ECN2)[1]	183.8353	183.5187	81.3000	14.6800
VL1(ECN4 - ECN3)[2]	91.9437	91.7744	81.2900	14.6500
VL2(ECN4 - ECN2)[3]	602.7124	602.7246	0.5400	7.6000
VL2(ECN4 - ECN3)[4]	203.0437	201.6934	0.5800	7.5700
VL3(ECN4 - ECN2)[5]	602.6584	602.7232	157.4700	7.1300
VL3(ECN4 - ECN3)[6]	203.0677	201.6906	160.3500	7.0500
VL5(ECN2 - ECN4)[7]	183.5132	27253.3649	6.7900	4997.7000
VL6(ECN3 - ECN4)[8]	91.7610	92.3172	4.8400	78.4000
VL7(ECN3 - ECN4)[9]	91.7655	92.0790	6.8900	84.0300

same egress resource with the injected failure messages are affected. Although the effect was profound, it was as a result of the buffering mechanism used in conflict resolution. In the case of standard Ethernet used in ETB/ECN specification, although logical isolations using VLANs were used in the experiment, the failure effects on latency and jitter were not contained in the first set of switches in which the frames traverses. Fault containment is appealing to safety criticality applications. Therefore TTEthenet is a top candidate for the underlying platform for TCN. On the availability of TSN implementation, future works will further evaluate its efficacy.

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REFERENCES

[1] Train Communication Network. Standard, International Electrotechnical Commission and others, Geneva, 1999.
[2] H. Kirrmann and P. A. Zuber. The iec/ieee train communication network. *IEEE Micro*, 21(2):81–92, March 2001.
[3] Mirko Jakovljevic, Arjan Geven, Astrit Ademaj, Georg Gaderer, Christian Fidi, Erik Männel, Jonas Rox, and Donatas Elvikis. Projet Safe4RAIL: Deliverable D1.1 -State-Of-The-Art Document on Drive-by-Datat. Research report, January 2017.
[4] SAFE4RAIL-1. Safe architecture for robust distributed application integration in roling stock, (accessed February 10, 2019). https://safe4rail.eul.
[5] J. Farkas, L. L. Bello, and C. Gunther. Time-sensitive networking standards. *IEEE Communications Standards Magazine*, 2(2):20–21, JUNE 2018.
[6] Time-triggered ethernet. Standard, Society of Automotive Engineers (SAE) International, 2011.
[7] Onwuchekwa Daniel and Obermaisser Roman. Fault injection framework for assessing fault containment of ttethernet against babbling idiot failures. In *2018 IEEE/ACM 26th International Symposium on Quality of Service (IWQoS)*, pages 1–6. IEEE, 2018.
[8] Jaehyun Park and Sangchul Lee. Performance evaluation of the train communication network. *IFAC Proceedings Volumes*, 31(32):155–160, 1998.
[9] Hyeon-Chyeol Hwang, Yong-Kuk Oh, and Ronny Yongho Kim. Performance evaluation of train propulsion control on ethernet network using truetime. In *IT Convergence and Security 2012*, pages 301–307. Springer, 2013.
[10] Hiroyuki Sugahara. Performance evaluation system of communication network for train control system using radio communication. *Quarterly Report of RTRI*, 56(3):187–193, 2015.
[11] Vaia Kalokidou, Stavros Typos, Evangelos Mellios, Angela Doufexi, and Andrew Nix. Performance evaluation of mmwave in 5g train communications. In *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 391–395. IEEE, 2018.
[12] Jianghua Feng, Xiangyang Lu, Weifeng Yang, and Jun Tang. Survey of development and application of train communication network. In Limin Jia, Zhigang Liu, Yong Qin, Rongjun Ding, and Lijun Diao, editors, *Proceedings of the 2015 International Conference on Electrical and Information Technologies for Rail Transportation*, pages 843–854, Berlin, Heidelberg, 2016. Springer Berlin Heidelberg.
[13] Hermann Kopetz. The rationale for time-triggered ethernet. In *2008 Real-Time Systems Symposium*, pages 3–11. IEEE, 2008.
[14] W. Steiner, G. Bauer, B. Hall, and M. Paulitsch. *Time-Triggered Communication*, chapter 8 : Time-triggered Ethernet In R. Obermaisser, Ed., pages 181–220. CRC press, Boca Raton, second edition, 2011.
[15] Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 2: Requirements for electrical/electronic/programmable electronic safety- related systems. Standard, International Electrotechnical Commission, Geneva, CH, April 2010.
[16] Kai Wang, Aidong Xu, and Hong Wang. Avoiding the babbling idiot failure in a communication system based on flexible time division multiple access: A bus guardian solution. In *2009 IEEE International Symposium on Industrial Electronics*, pages 1292–1297. IEEE, 2009.
[17] Aircraft Data Network Part 7, Avionic Full Duplex Switched Ethernet (AFDX) Network. Standard, Aeronautical Radio, INC., Maryland, june 2005.
[18] Rodrigo Ferreira Coelho. *Buffer Analysis and Message Scheduling for Real-time Networks*. PhD thesis, Technische Universität Kaiserslautern, 2017.