GETDEN EXECUTIVE SUMMARY REPORT

GETDEN

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1. INTRODUCTION

1.1. PURPOSE

The present document exposes the Executive Summary Report for the activities related to the "Gigabit Ethernet TSN DEtermnisitc Network (GETDEN)".

The report covers the scope of the activity, including the objectives, literature survey, definition of the solution, validation plan, main results obtained, conclusions and roadmap.

1.2. SCOPE

This document is a deliverable by GMV as part of the Additional Deliveries at FP, in the frame of the "Gigabit Ethernet TSN DEtermnisitc Network (GETDEN)".

1.3. DEFINITIONS AND ACRONYMS

1.3.1. DEFINITIONS

Concepts and terms used in this document and needing a definition are included in Table 1-1.

Table 1-1 Definitions

Concept / Term	Definition

1.3.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 Acronyms

Acronym	Definition
AD	Applicable Document
AIV	Assembly Integration & Verification
COTS	Commercial Off-The-Shelf
ECSS	European Cooperation on Space Standardization
FPGA	Field-Programmable Gate Array
HW	Hardware
ID	Identification Number
IP	Intellectual Property
OS	Operating System
PL	Programmable Load
PS	Processing System
RD	Reference Document
RT	Real Time
RTEMS	Real-Time Executive for Multiprocessor Systems
RTOS	Real Time Operating System
SoC	System on Chip
SW	Software
TSN	Time Sensitive Network
VHDL	VHSIC HDL
VHSIC	Very High Speed Integrated Circuit

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.-1]	Detailed Proposal – GETDEN	-	1.0	24/04/2017

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.-1]	STATEMENT OF WORK FOR THE ESA INNOVATION TRIANGLE INITIATIVE (ITI)	ESA-TRP-TECTI-SOW-004127	-	27/01/2017
[RD.-2]	TN01 GETDEN REQUIREMENTS AND ARCHITECTURE	GETDEN-TN01	3.0	30/04/2019
[RD.-3]	TN02 GETDEN DESIGN AND DEVELOPMENT REPORT	GETDEN-TN02	1.1	16/05/2019
[RD.-4]	TN03 GETDEN DEMONSTRATION RESULTS AND ROADMAP	GETDEN-TN03	1.0	26/11/2019
[RD.-5]	http://www.ohwr.org/projects/white-rabbit/wiki	-	-	-
[RD.-6]	https://www.tttech.com/news-events/newsroom/details/development-agreement-between-tttech-and-airbus-safran-launchers/	-	-	-
[RD.-7]	Comparison of Communication Architectures for Spacecraft Modular Avionics Systems	NASA/TM—2006–214431	-	June 2006
[RD.-8]	Guillermo Ortega (ESA), Johann Bals (DLR), Michele Delpech (CNES), Avionics Systems Technology for New Exploration Scenarios, 10th ADCSS Avionics Workshop	-	-	20/10/2016
[RD.-9]	TN03: OSRA communication network specification	OSRA-NET_TN03	1.0	24/04/2017

3. FINAL REPORT

3.1. GETDEN CONTEXT AND MAIN OBJECTIVES

The activity of "Gigabit Ethernet TSN Deterministic Network (GETDEN)" as part of the Innovative Triangle Initiative frame, has the main objective of providing a low-cost yet space-grade data bus solution based on open-source and standard technologies, already identified and implemented in other non-space domains.

Figure 3-1 GETDEN Consortium and Frame

The innovation content of GETDEN lies in the spin-in of a non-space technology which has already been demonstrated in highly demanding applications (such as the White Rabbit project at CERN [RD.-5]), enabling therefore to implement high throughput on-board data buses with a strict determinism with COTS HW and SW elements while ensuring high reliability, hence dramatically reducing avionic subsystem costs.

The expected result of this activity is to develop a standard and low cost communication bus alternative to the historical data bus (MIL-1553B) and other new fast buses (as TTEthernet) fulfilling the bus communication requirements for the microlauncher avionics. The identified solution will be based on the Time Sensitive Network (TSN) Gigabit standard, which is a public and interoperable standard, allowing open HW/SW solutions, avoiding vendor lock-in and using standard Ethernet components and standard IT traffic.

A number of potential applications in different avionics architectures have been identified either in commercial markets (i.e. space transportation systems, telecom satellites) either in scientific experiments (high throughput payloads for scientific mission) and the implementation on micro-launcher has been considered the most representative above all, in terms of 'determinism' needs. In next steps, new space applications will be exploited.

3.2. LITERATURE SURVEY ON COMMUNICATION BUS FOR CRITICAL APPLICATIONS

The historical data bus MIL-STD 1553B is the almost de-facto standard used up to now for launcher avionics. Main drawbacks of MIL-STD-1553B are the high cost and low speed (1 Mbps), which can be a major obstacle to enable advanced functionalities, including reusability of stages.

Table 3-1 provides a one-glance trade-off feedback of the identified alternatives for current on-board data buses and their application for a microlauncher scenario. MIL-STD 1553B and CAN bus are discarded due to high cost and low speed. SpW, SpaceFibre, TTEthernet and EtherCAT rely on high cost implementations and are vendor locked solutions. In case of microlaunchers, where cost minimisation is of the essence, this results into a major drawback.

Criteria	MIL-STD 1553B	CAN (CAN FD)	TTEthernet	SpaceWire	SpaceFibre	Standard GigaEthernet	TSN GigaEthernet
Cost	--	+	--	--	---	++	**++**
Speed	- 1 Mbps	- 1 Mbps (8 Mbps)	++ 100/1000 Mbps	++ 200 Mbps	+++ 2,500 Mbps	+++ 1,000-10,000 Mbps	**+++ 1,000-10,000 Mbps**
Determinism /Reliability	++	++	++	++	++	-	**++**
Cables Length (at max speed)	+ 6.1m for transformer coupled stubs	+ 40m	++ 200m	- 10m	++ 100m (expected)	++ 200m	**++ 200m**
Scalability	++	++	++	+	+	+++	**+++**

Table 3-1 Communication Buses Comparison

Thanks to TSN, standard Ethernet will now be able to cover all fieldbus-related requirements, making fieldbuses and their Ethernet-based successors like EtherCAT entirely superfluous. Time-Sensitive Networking (TSN) is a novel technology that combines the large bandwidth capabilities of Ethernet with the determinism of a real-time fieldbus – all based on vendor-neutral standards specified by the IEEE 802 and delivers a high level of determinism in standard IEEE 802.1 and IEEE 802.3 Ethernet networks. Since TSN is not a proprietary system like many other established real-time solutions, it can be used with devices from different manufacturers.

In the frame of GETDEN study, the applicability of the OSRA requirements is analyzed with a very high level of compliance as conclusion. The idea behind OSRA is to identify and define a 'communication layer' independent from the technology, avoiding to write requirements that are technology-dependent.

3.3. REQUIREMENTS DEFINITION AND DESIGN DEFINITION OF GETDEN-TSN

The requirements for the GETDEN-TSN implementation are focused is general space applications, and focused in microlaunchers scenario. Therefore the requirements are defined according common needs in the frame of microlaunchers and space applications.

Additionally, the ARION-1 microlauncher is identified as the first use case scenario of the GETDEN-TSN. Since GETDEN-TSN scope is to cover general microlaunchers requirements, the TSN bus communication will be properly adapted to the ARION-1 requirements in the frame of the AVIOAR1 project.

As summary of the general requirements definition, the following main topics are fully covered:

- The communication bus is an open SW/HW solution and interoperable standard, avoiding vendor lock-in solutions, using standard Ethernet components and standard IT traffic.
- The GETDEN-TSN solution is based on COTS elements
- The GETDEN-TSN solution is open to potential adaptations for bigger networks (higher number of nodes, higher bus loads, different topologies and reconfiguration needs) with overall bus length of 40 meters and 15 nodes.
- The GETDEN-TSN solution supports ring topologies, easily reconfigurable and resizable.
- The GETDEN-TSN solution supports Reliable and Fault-tolerant net topologies
- The GETDEN-TSN validation is based on validation of timing, latencies, bandwidth, determinism, scheduled traffic, priorities, frame pre-emption and fault-tolerant topology.
- The GETDEN-TSN solution is based on Gigabit Ethernet 1000Base-T, able to guarantee high bandwidth (100 Mbps).
- The GETDEN-TSN solution supports synchronized reserved/scheduled traffic with different kind of priority traffic (high priority and best effort) standardized by VLAN tagging (IEEE 802.1Q).
- The GETDEN-TSN solution provides:
  - Network synchronization uncertainty below 10 µs.
  - Determinism at 50us.
  - Latency within 10 hops of less than 0.5ms.

  - jitter of less than 0.5us per hop.
  - In general this figure can be considered suitable also for generic space applications. But the value is reduced for specific case time critical (landers) or used for particular payload (high precision).
- The GETDEN-TSN solution supports basic features related to:
  - Timing and synchronization (802.1AS-REV)
  - Frame Preemption and queuing (802.1Qbu/Qbr)
  - Traffic Shaping for time sensitive data streams (802.1Qbv)
  - Redundancy protocol based on ring-topologies (IEEE 802.1CB protocols) allowing zero recovery time and low-cost redundancy.
- The GETDEN-TSN software elements (GPTP module and API) are implemented in the RTEMS v5 SMP as real-time operating system

The GETDEN-TSN system architecture consists on a number of software and gateware-based components to provide the required TSN functionalities. GETDEN-TSN System, hosted on a Xilinx Zynq-7000 SoC hardware platform, comprised by a hardened, dual-core ARM-based Processing System (PS) and a Programmable Logic (PL) fabric, where dedicated gateware is mapped.

Table 3-2 introduces the different processing system (PS) or programmable logic (PL) architecture elements, attending to the aforementioned functional subsystems.

Acronym	Full Name	Impl.	Brief explanation
GETDEN-TSN Subsystem			
VLAN	TSN VLAN Module	PL	IEEE 802.1Q tagging and untagging. Redirection management
TAS	Time-Aware traffic Shaper	PL	Transmitting traffic priorization and static cyclic scheduling
TSN GW API	TSN Gateware API	PS	User configuration and management of TSN functionalities
Redirector		PL	Internal commutation matrix between PS, user logic modules and Ethernet interfaces
GETDEN-Networking Subsystem			
DMA	Xilinx DMA Module	PL	Provides access from/to frame buffer memory area
MAC	Xilinx Ethernet MAC	PL	Medium Access Control module provided by Xilinx
Driver	RTEMS Network Driver	PS	Interfaces with RTMES Network API. Configuration and management of Networking modules
GETDEN-Timing Subsystem			
gPTP	generilized Precision Time Protocol Algorithm	PS	Local implementation of the IEEE 802.1AS protocol
gPTP API	gPTP API	PS	Enables configuration and monitoring of time synchronization
PHC	PTP Hardware Clock	PL	Stores local time and eases time synchronization and distribution

Table 3-2 GETDEN-TSN architecture elements

Figure 3-2 depicts these functional elements under GETDEN-TSN architecture and their interactions with Ethernet traffic (blue arrows) and time distribution (brown arrows) flows. GETDEN-TSN (blue) GETDEN-Networking (green) and GETDEN-Timing (orange) subsystem elements are differentiated.

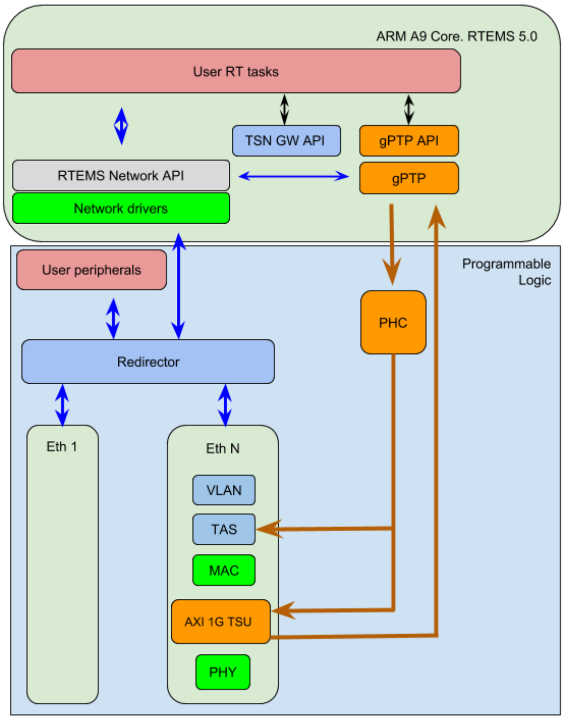

Figure 3-2 Functional description of TSN system architecture.

3.4. GETDEN-TSN TEST PLAN DEFINITION AND RESULTS OBTAINED

In order to validate the GETDEN-TSN implementation, a Test Plan is defined. The GETDEN-TSN Test Plan validates incrementally and step by step all the modules implementation (unitary testing), the interaction between the modules (integration testing) and the system performances (system testing).

The following subsections provides summarizes each test, including purposes, and successful results.

As conclusion, the GETDEN-TSN implementation has been fully validated for time critical communications in the space applications.

3.4.1. UNITARY TESTS

The scope of unitary allowed to validate the different functional elements of GETDEN and achieve the first requirements. In particular:

1. The **high bandwidth** guarantee test showed that GETDEN is 1000-Base-T compliant and therefore accomplishes stated requirements.
2. The **determinism and latency** test probed point to point latency and determinism. This test shows the feasibility of accomplishing the demanded 0.5 ms of determinism in 10 hops.
3. The **priority traffic** test is focused to probe the differentiation and prioritization capabilities, as required.
4. The **network reconfiguration** test demonstrates the capability of the IEEE 802.1AS Best Master Clock Algorithm (BMCA) implementation to provide fast switchover of the network time reference as well as to provide dynamic reconfiguration of the different time-aware interfaces on each node.
5. The **ring topology** tests shows the ability of the solution to support redundant links and keep synched in case of link failure.
6. The **main ring network resize** test shows the recovery capability driven by the BMCA and the programmable logic required supporting synchronization accuracy.
7. The **time distribution** tests demonstrates the support of the solution to synchronize all the nodes of the network with a span below of ±50 ns.
8. The **timestamping** test shows the support of the solution to provide accurate ingress and egress time of desired Ethernet packets.
9. The **VLAN tagging** test show the GETDEN capability of identify user time-sensitive traffics and provide them standard differentiation and prioritization.

10. The **Time Aware Traffic Shaper** test shows the support of the solution to perform a time-driven cyclic schedule.
11. The **frame preemption** test. This mechanism described on IEEE 802.1Qbu and IEEE 802.3br minimizes guard bands thus allowing better effective bandwidth.
12. The **seamless redundancy** test is key to demonstrate the reliability and fault-tolerance of GETDEN. Seamless redundancy on GETDEN accomplishes IEEE 802.1cb FRER protocol and provides TSN stream oriented zero-time switchover in case of a network element failure.

3.4.2. INTEGRATION TESTS

The integration tests have been used to probe the integration between the different sub-modules.

The **synchronized scheduled traffic** and the **heterogeneous traffic support** have been some of the requirements tested in this section.

The **redirector module** is needed for packet routing in complex deployments. In **TSN subsystem integration** test, it has been verified that all the main TSN modules (VLAN, TAS) work correctly and the **timing distribution** correctly **synchronizes** all the nodes.

Finally the seamless **redundancy support**, which makes the network tolerant to failures and to cuts of some links, has been successfully tested.

3.4.3. SYSTEM TESTS

The system tests demonstrate that the fully integrated GETDEN architecture is capable of achieving the project requirements on real scenarios:

The end-to-end determinism capability test showed how the different architectural elements cooperate on the determinism capability, by precisely describing the latency introduced by each one.

1. The **end-to-end seamless redundancy** test probes the GETDEN-TSN reliability for time-critical traffics.
2. The **gPTP network synchronization** test probes that the span of synchronization is below of the range of ±50 ns.
3. The **short loss of gPTP** test demonstrates the synchronization reliability provided by the IEEE 802.1AS against punctual losses.
4. The **babbling-idiot failure** test probes the reliability provided by GETDEN against network element failures. The babbling-idiot test is aligned with REQ-08.
5. The **delay of some of the links** test showed that the synchronization accuracy is not affected by the propagation time on the link, but on its variability.
6. The last test is a **demonstration of representative satellite mission scenario** which gathers all the implemented functionalities in a realistic setup. The results of this test are mainly focused on the reliability, determinism for synchronous traffics and heterogeneous traffic convergence provided by GETDEN-TSN. The frame-preemption capability was used to protect time-critical traffics against best effort ones. Furthermore this test was presented in situ at ESTEC (Noordwijk), as part of the final demo.

3.5. GETDEN-TSN ROADMAP

GETDEN activity has demonstrated the suitability of TSN light implementation for time critical communications in the space applications. For what regards the identification of requirements, it can be concluded that a complete set of requirements has been identified together with their verification methods.
Also a proper cross-comparison of GETDEN requirements with state-of-the-art requirements for space application ([RD.-9]) has been carried out. Thus in terms of requirements it can be concluded that a concrete effort has already been done and a self standing set of requirements that can be common to different applications are already in place.
The implementation is also in place, and it has been properly verified and it has been proved to be working according to an accurate validation plan.

Nevertheless a roadmap for future implementation and applications but also improvements can be identified, therefore hereafter some ideas are proposed. They are proposed in an hypothetical order of execution, although some of them can be run in parallel.

- Validation with different use cases

Original high level functional requirements of GETDEN activity, in the original ITI proposal, were thought to be relevant and encompass for different kind of applications, from launchers to satellite platform to payload experiment or robotics application. Network topology, type of nodes, type of traffic and amount of traffic were considered as much as possible encompassing all these different application. Nevertheless at the stage of verification, it was necessary to choose a use case and this was straightforward the micro-launcher use case due to the parallel development of the avionics that was carried out by GMV in the same timeframe.

In order to continue proving the suitability of GETDEN IPCORE for space applications, it would be a good exercise to identify other use cases and to perform a delta validation for those applications according to their peculiar traffic configuration.

- Compatibility with other TSN implementations ('TSN for Space' Working Group)

Standardization is used to allow communication and compatibility between different implementation of the same standard. TSN standard suite is larger than the one used for GETDEN because it refers to the complete stack ISO/OSI while in this application only first layers are implemented and also not with all their functionalities. Therefore it would be interesting to identify some rules/requirements for a guidelines of interoperability between different applications. A TSN working group ('TSN for Space') with representatives from the different industries that are working on TSN implementation could be an interesting starting point for the study.

- Different HW platform

GETDEN IPCORE has been developed and verified on a COTS Zynq platform. Zynq COTS is currently used in some application for space (i. e. some cubesat) but it is not the baseline for classical mission where radiation hardness and/or radiation tolerance are important aspects to be taken into account for the reliability of the system in its environment. Therefore it would be interesting to study its implementation in a rad-hard chip or with a rad-tolerant approach.

- In-flight validation

In-flight validation is an added value for the final proof of the concept of a new technology. It is already foreseen that GETDEN IPCORE for micro-launcher will fly for the first time with MIURA 1 in 2020. But it would be interesting to find other applications/platform to have a first demonstration in flight. For example there are several cubesat already flying with COTS elements like Zynq platform and it would be interesting to embed in their platform an experiment with a bus communication based on an TSN light implementation.

END OF DOCUMENT