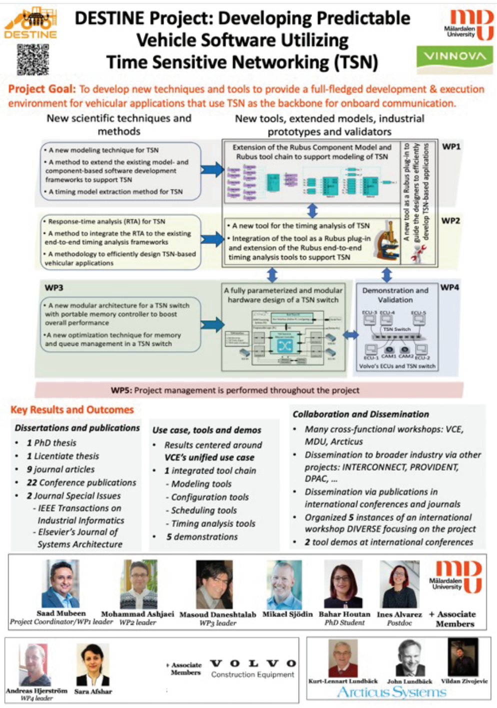
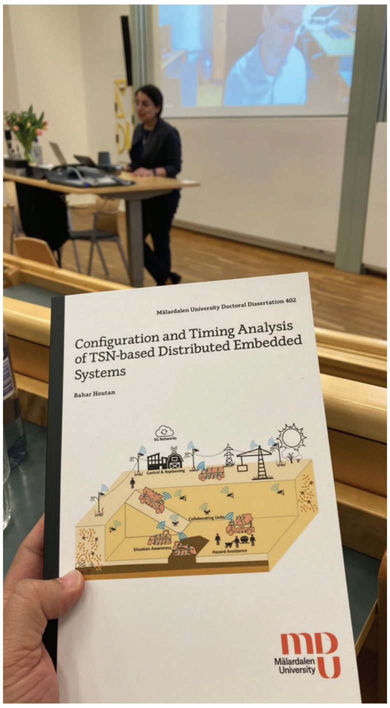
Project title

Public report





Project within FFI- Elektronik, mjukvara och kommunikation
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Date 2024.03.31

Content

1. Summary

The latest developments in automotive technology, particularly in the segment of autonomous vehicles, have led to significant enhancements in functionality and new customer features. These advancements heavily depend on data-intensive processing, necessitating substantial computational power and high-bandwidth onboard real-time communication systems. These requirements are expected to increase further, driven by innovation in the contemporary and future vehicle architectures. While there is a lot of research done to meet the challenge of computational requirements, relatively small efforts have been spent to deal with the challenge of supporting the communication requirements. To support the high-bandwidth low-latency onboard real-time communication in modern vehicles, the IEEE Time-Sensitive Networking (TSN) task group has developed a set of standards targeting different classes of real-time traffic, support for time-triggered traffic at the same time as non-real-time traffic, support for resource reservation for different classes of traffic, support for clock synchronization, and providing several traffic shapers. However, a complete development environment that supports modelling, timing analysis, configuration, simulation, and execution for vehicular applications that use TSN was missing from the state of the art prior to this project. Since TSN is a complex technology with many features and configuration possibilities; taking full advantage of TSN in the development of complex vehicular functions encountered as a daunting challenge.

To address these challenges, DESTINE project developed innovative techniques, methods, and prototypes to provide a full-fledged development environment for vehicular applications that use TSN as the backbone for onboard communication. The project results support modelling, timing and resource analysis, simulation, configuration, optimisation, and execution of end-to-end behaviour of complex functions deployed in a heterogeneous environment connected by a TSN backbone. The project results were validated and their industry usability demonstrated through two key approaches: (i) implementing and applying newly developed scientific techniques and tool prototypes to a unified use-case demonstrator in the automotive industry, and (ii) creating a methodology and guidelines for end-users (such as application developers in the vehicle industry) to efficiently utilize the project results by designing TSN-based vehicular applications, taking into account resource utilization, legacy network protocols, and traffic properties.

The project consortium consisted of three partners including the main applicant Mälardalen University (MDU), Volvo Construction Equipment (Volvo CE) and Arcticus Systems. A proof of concept for these novel techniques is provided by extending the Rubus Component Model (RCM) and Rubus-ICE tool chain. RCM and Rubus-ICE, developed by Arcticus, have been used in the vehicle industry for over 25 years, e.g., by Volvo and BAE Systems, among others. One unique characteristic of this consortium is that it offers a clear value chain from academia (MDU), who developed the new scientific techniques and methods; through the tool developer/vendor (Arcticus), who implement the techniques as tool prototypes and then integrated the prototypes to their tool chain; to the end user of the technology (Volvo CE), who used the tools and the new development methods on their industrial use case; back-propagation of the feedback on usability for their refinement.

The project results were encapsulated in 35 publications (1 PhD thesis, 1 Licentiate thesis, 9 journals, 2 Guest Editorials, 22 conference). Some of these publications include sceintific reviews together with our findings on industrial requirements and worst-case scenarios as well as the results obtained during the project in state-of-the-art publications in high-ranked international journals. Furthermore, we coordinated the publication of two editorials in international journals focusing on the project's theme. In addition, the project developed 4 tool prototypes and 1 industrial use-case demonstrator. The project results have been disseminated to a broader audience, beyond the scientific publications. We have organized five editions of an international Workshop on Advanced Technologies in Vehicular Systems (DIVERSE) on the project's theme. All editions of the workshop were located at the international conference on Emerging Technologies and Factory Automation (ETFA) 2019-2024 respectively. The workshop featured invited presenters from academia and industry in the vehicular domain. Using industrial seminars and trainings on TSN, workshops, and other industrial collaboration projects, we have already shared the project results with the industry both within Sweden and abroad, e.g., Ericsson, ABB, HIAB, VGTT, Westermo, TCN, Thales, to mention a few.

2. Sammanfattning på svenska

De senaste framstegen inom fordonsteknik, särskilt i autonoma fordon, är starkt beroende av dataintensiv bearbetning. Dessa innovationer kräver betydande beräkningskraft och inbyggda kommunikationssystem med hög bandbredd. Även om forskningen har fokuserat på beräkningsutmaningar, är det fortfarande relativt understuderat att ta itu med kommunikationskrav. Arbetsgruppen IEEE Time-Sensitive Networking (TSN) har utvecklat standarder för realtidstrafik, resursreservation, klocksynkronisering och trafikformning. En omfattande utvecklingsmiljö som stöder TSN för fordonsapplikationer saknades dock fram till detta projekt. Att utnyttja TSN:s komplexa funktioner innebär en formidabel utmaning när det gäller att utveckla komplicerade fordonsfunktioner. DESTINE-projektet tog sig an dessa utmaningar genom att utveckla innovativa tekniker och prototyper för fordonstillämpningar som använder TSN som kommunikationsryggraden. I detta sammanhang har projektet underlättat modellering, timinganalys, simulering och optimering av komplexa mjukvarufunktioner som är distribuerade över ett TSN-nätverk. Branschens användbarhet demonstrerades genom två tillvägagångssätt: (i) att tillämpa vetenskaplig teknik på en demonstrator för användningsfall för fordon, och (ii) skapa riktlinjer för effektiv design av TSN-baserade fordonstillämpningar av slutanvändare, med hänsyn till resursanvändning och äldre nätverksprotokoll.

Projektkonsortiet bestod av Mälardalens högskola (MDU), Volvo Construction Equipment (Volvo CE) och Arcticus Systems. En unik egenskap hos detta konsortium är att det erbjuder en tydlig värdekedja från akademin (MDU), som utvecklat de nya vetenskapliga teknikerna och metoderna; genom verktygsutvecklaren/leverantören (Arcticus), som implementerar teknikerna som verktygsprototyper och sedan integrerade prototyperna i sin verktygskedja; och slutligen till slutanvändaren av tekniken (Volvo CE), som använde verktygen och de nya utvecklingsmetoderna i sitt industriella användningsfall. Projektresultaten var inkapslade i 35 publikationer (1 doktorsavhandling, 1 licentiatavhandling, 9 tidskrifter, 2 gästredaktioner, 22 konferenser). Några av dessa publikationer inkluderar vetenskapliga översikter tillsammans med våra rön om industriella krav och värsta tänkbara scenarier samt de resultat som erhållits under projektet i toppmoderna publikationer i högt rankade internationella tidskrifter. Vidare samordnade vi publiceringen av två ledare i internationella tidskrifter med fokus på projektets tema. Dessutom utvecklade projektet fyra verktygsprototyper och en demonstrator för industriellt bruk. Projektresultaten har spridits till en bredare publik, bortom vetenskapliga publikationer. Vi har organiserat fem upplagor av en internationell Workshop on Advanced Technologies in Vehicular Systems (DIVERSE) på projektets tema. Workshopen innehöll inbjudna föredragshållare från akademi och industri inom fordonsdomänen. Med hjälp av industriseminarier och utbildningar om TSN, workshops och andra industriella samarbetsprojekt har vi redan delat projektresultaten med industrin både inom Sverige och utomlands.

3. Background

Contemporary vehicles are increasingly reliant on advanced features and functionalities, necessitating high levels of computational capabilities. This is largely due to the use of data-intensive sensors, such as video cameras, radars, lidars, and ultrasonic sensors. These elements require complex coordination and high-bandwidth communication between the computing units, also known as Electronic Control Units (ECUs). As vehicle architectures continue to evolve and innovate, these requirements are projected to escalate. To meet these demands, the research community propose the use of powerful ECUs, interconnected by high-bandwidth onboard communication networks [J3][2]. There are many existing works that provide software development techniques focusing on modelling, timing analysis, deployment and execution of vehicular applications on powerful ECUs (e.g., multi-core processors) that are connected by low-bandwidth onboard real-time networks such as Controller Area Network (CAN) [3]. With the advent of high data-rate sensors and advanced features in modern vehicles, the traditional low-bandwidth onboard real-time communication (based on field buses) is becoming a bottleneck. Hence, there is an urgent need for high-bandwidth and low-latency onboard real-time communication to develop advanced vehicle features in a cost-effective and reliable way.

Prior to the initiation of this project, there was a noticeable scarcity of development environments tailored for vehicular applications that require high-bandwidth onboard real-time communication [4][5][6]. One notable exception was Audio/Video Bridging (AVB) [7], which is a set of IEEE standards supporting high-bandwidth (up to 100 Mbit/s) real-time communication. While AVB provides high bandwidth, it does not support low-latency onboard communication that is required by time-sensitive control messages. In order to support the high-bandwidth and low-latency onboard real-time communication, the IEEE Time-Sensitive Networking (TSN) task group [7][8][9] developed a set of standards. The architectures that are based on the TSN standards have become promising solutions in various domains due to the features of TSN such as support for different classes of real-time traffic, time-triggered traffic and non-real-time traffic, resource reservation for different classes of traffic, clock synchronization, and traffic shaping.

The release of the TSN standards by the IEEE has sparked a huge interest in its utilization, not only in the Swedish vehicle industry but also in many international Original Equipment Manufacturers (OEMs). This is evident from their active participation in national and international workshops exclusively on TSN (DESTINE consortium was also formed in one of the international workshops on TSN). The biggest challenge faced by the OEMs in utilizing TSN in their products is the lack of a full-fledged tool support to model, timing analyse, deploy, and execute TSN-based vehicular applications. Given the tool support, another challenge faced by the industry is the lack of guidelines for developing these applications in an efficient and cost-effective manner. We identified that none of the existing works, prior to this project, provided a full-fledged model-based software development environment for TSN. Such an environment is vital for the vehicle industry in developing the applications that utilize TSN for onboard communication.

4. Purpose, research questions and method

In this project, we envisioned the development environment to consist of new techniques for modelling the software architecture, timing analysis to verify timing predictability[1], designing and configuring switches to match the evolving TSN standards, deploying and executing TSN-based vehicular applications. Our aim was to create techniques for modelling and analysing software functions that utilize Time-Sensitive Networking (TSN), with a focus on verifying their timing properties. We envisioned an environment supplemented with a tool chain that realizes these techniques. To showcase the practicality of our techniques in real-world settings, we also planned to develop a proof-of-concept prototypes and demonstrators. The envisioned workflow in this project and the aimed scientific techniques, prototypes and industrial demonstrators are depicted in Figure 1.

4.1 Research challenges

There are four key Research Challenges (RC_X) that need to be addressed in achieving the project goals.

RC_1: The first key research challenge is to develop a new modelling technique for TSN that can be incorporated into the existing model- and component-based software development frameworks in the vehicle domain. The technique is targeted to be expressive enough to allow extraction of timing models to perform the end-to-end timing analysis of TSN-based distributed vehicular applications.

[1]A system is time predictable if it is possible to prove before running the system that all timing requirements are satisfied **Error! Reference source not found.**.

RC₂: The second key research challenge is to develop response-time analysis for TSN considering different variations in the standards. In addition, the challenge of integrating the developed analysis to the state-of-the-art end-to-end timing analysis framework for distributed vehicular applications needs to be addressed.

RC_3: Given the modelling and timing analysis techniques developed in response to RC_1 and RC_2, develop a methodology to guide the application developer for efficiently designing the TSN-based applications with a better view on resource utilization considering legacy network protocols and traffic properties.

RC_4: As the TSN standards are evolving, a key challenge in hardware realization of TSN is to develop techniques related to the TSN architecture that allow upgrading the hardware in a short time. The scalability of TSN switches is another challenge when the number of ports increases, which significantly affects the memory bandwidth. This necessitates implementing optimized memory interface for the TSN switch fabric.

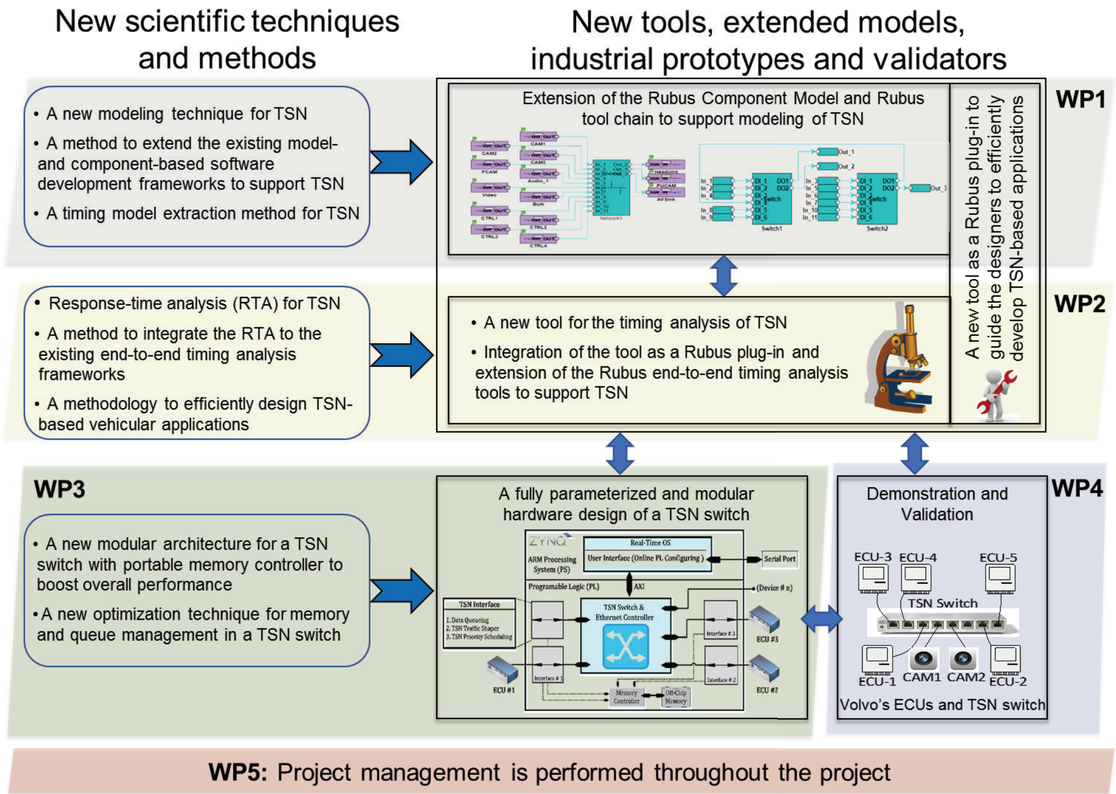

Figure 1. Envisioned workflow in the DESTINE project: new scientific techniques and methods are depicted on the left, while new tools, models, prototypes, and validators are shown on the right.

4.2 Scientific method

Given the project goals and expected outcomes (techniques, methods, frameworks and proof-of-concept prototypes), the Systems Development Research Method [10] suits well to this project. Using this method, first, we will construct a conceptual framework based on our key research challenges and relevant state-of-the-art literature. This step will generate new ideas, concepts, theories, techniques, and methods. In the second step, system requirements, assumptions, architecture, functionalities, relationship, and interactions among the system components will be defined. The system will be designed and analysed in the third step. In this regard, the studied domain knowledge will be applied to develop new and alternative techniques and solutions. After evaluating these solutions with respect to the requirements, the best performing solution will be selected. Using the selected solution, one or more prototypes of the system will be developed, experimented, analysed and evaluated. In the case of unsatisfactory outcomes of any step, the research method allows going back to any previous step to perform the desired changes or optimizations. Moreover, the whole process can be iterated to get the desired or optimized outcomes. The results and experiences from this research method can be generalized and used to develop similar systems. Although this method was developed in 1990, it continues to work very well in research projects that aim at developing techniques, methods, and prototypes to be used or transferred to the industry. The members of DESTINE have already used this research method successfully in several research and technology transfer projects [11].

5. Objective

The overall objective of this project is to develop new techniques, methods, and tools to provide a full-fledged development and execution environment for vehicular applications that use TSN as the backbone for onboard real-time communication as shown in Fig. 1.

The overall objective of the project is realized with the following four goals (G_X):

G_1: Develop a new modelling technique for TSN. Integrate the new technique to the state-of-the-art model- and component-based software development frameworks for distributed vehicular applications.

G_2: Provide a support to verify predictability by developing timing analysis for TSN considering different variations in the standards. Integrate the newly developed analysis to the state-of-the-art end-to-end timing analysis framework for distributed vehicular applications. Further, develop a methodology to provide guidelines to efficiently design TSN-based applications with a better view on resource utilization considering legacy network protocols and traffic properties.

G_3: Develop a fully parameterized and modular hardware design of a TSN switch and prototype it on a Field Programmable Gate Array (FPGA). Moreover, design a smart memory management unit to cope with the memory bandwidth limit with increasing number of ports in the TSN switch.

G_4: Provide a proof-of-concept by implementing the newly developed techniques and methods in an existing component model and tool chain, namely Rubus [11]. Using the extended component model and tool chain, develop prototypes in the industrial settings by modelling, analysing, deploying, and executing vehicular applications on real ECUs that are connected by a TSN switch.

There are four key Research Challenges (RCs) that need to be addressed in achieving the project goals.

RC1: The first key research challenge is to develop a new modelling technique for TSN that can be incorporated into the existing model- and component-based software development frameworks in the vehicle domain. The technique is targeted to be expressive enough to allow extraction of timing models to perform the end-to-end timing analysis of TSN-based distributed vehicular applications.

RC2: The second key research challenge is to develop response-time analysis for TSN considering different variations in the standards. In addition, the challenge of integrating the developed analysis to the state-of-the-art end-to-end timing analysis framework for distributed vehicular applications needs to be addressed.

RC3: Given the modelling and timing analysis techniques developed in response to RC1 and RC2, develop a methodology to guide the application developer for efficiently designing the TSN-based applications with a better view on resource utilization considering legacy network protocols and traffic properties.

RC4: As the TSN standards are evolving, a key challenge in hardware realization of TSN is to develop techniques related to the TSN architecture that allow upgrading the hardware in a short time. The scalability of TSN switches is another challenge when the number of ports increases, which significantly affects the memory bandwidth. This necessitates implementing optimized memory interface for the TSN switch fabric.

6. Results and deliverables

The project results provide new knowledge that extends state of the art in model-based software development, schedulability analysis and resource optimization of real-time networks in the embedded systems domain in general and in the vehicular domain in particular. The scientific results are achieved in the form of new scientific techniques, methods, and proof-of-concept prototypes that support modelling, analysis and configuration of predictable distributed software applications that utilize TSN. The project results also have a considerable impact on the state of the practice in the vehicular domain with regards to new and extended industrial tools, development models, prototypes, and industrial use-case demonstrators. Given these new techniques and tools, the results also include a methodology to guide the vehicle application designer to develop TSN-based applications in a resource-efficient manner. This, in turn, helps in enhancing the development skills of the vehicle application designers.

6.1 Deliverables and goals fulfilment

The project plan included 17 deliverables: 2 journal articles, 10 conference/workshop papers, 1 internal technical report, 3 tool/design prototypes, 1 integrated demo. The project achieved significantly higher number of contributions in this regard. This is evident from the fact that the project results are encapsulated in 35 publications (1 PhD thesis, 1 Licentiate thesis, 9 journals, 2 Guest Editorials, 22 conference), 4 tool prototypes and integrated industrial use-case demonstration.

The goal fulfilment in the project is described according to the fulfilment of the goals (G) and research challenges (RC) as follows.

The first goal, G_1, and first research challenge, RC_1, are addressed by: (i) developing a holistic modelling technique for TSN [C20, C21], (ii) integrating the modelling technique with a model- based software development environment [C3, C12, J5], (iii) developing a comprehensive end-to-end timing model that incorporates TSN communication [C3, C7].

The second goal, G_2, related to the second research challenge, RC_2, is addressed by: (i) developing a response-time analysis for TSN including all traffic classes [J6, J7, C10, C16], (ii) developing an end-to-end timing analysis framework for TSN-based distributed embedded systems [J1, C3].

The second goal, G_2, related to the third research challenge, RC_3, is addressed by: (i) developing and refining a TSN simulator to assist the design methodology [C12], (ii) analysing and discussing implications of various design choices in TSN [J2], (iii) investigating and analysing several heuristics for designing various traffic in TSN [J4, C5, C9, C11, C13, C14], (iv) utilising the analysis results to guide the development [C8, C9, C11, C12], (v) guidelines for the developers to reserve resources in the TSN network using a new bandwidth reservation analysis for schedulability of AVB Traffic in TSN [C1], and (v) supporting a centralised network configuration of TSN networks [C2, C4, C6].

The third goal, G_3, and the fourth research challenge, RC_4, are addressed by: (i) designing a reconfigurable micro-architecture hardware on FPGA in the form of a low-overhead, efficient and fault-tolerant mechanism for reliable on-chip router [C19, J8], (ii) developing a novel frame preemption model in TSN [J4], (iii) demonstrating the industrial use case on TSN hardware [Final demonstrator at Volvo CE].

The fourth goal, G_4, is addressed by: (i) developing a prototype of the modelling technique for TSN and the software development framework in the Rubus Component Model and tool chain [J5, C3, C15, C17], (ii) developing a prototype of response time analysis for TSN and integrating it to the Rubus tool chain [J1, C3, C7, C17], (iii) developing a prototype of the end-to-end timing analysis for TSN-based distributed software systems and integrating it to the Rubus tool chain [J1], (iv) developing a prototype of the configuration framework [C2, C4, C6, C12], and (v) validation and demonstration of developed scientific techniques and prototypes on a unified use-case demonstrator in the automotive industry [C17, C18, C22, final demonstrator at Volvo CE].

Additionally, we published state-of-the-art reviews, also presenting our findings on industrial requirements and worst-case scenarios, alongside the results obtained during the project, in state of the art publications in high-ranked international journals [J3, J9]. Furthermore, we coordinated the publication of two editorials in international journals focusing on the project's theme [GE1, GE2].

6.2 Relevance to the programme objectives

In the vehicle industrial domain, there is a market-driven urgent need to deploy high-bandwidth and low-latency in-vehicle communication to support advanced data-intensive functionalities, especially in the segment of autonomous vehicles. DESTINE focused on multiple levels of vehicular application development, i.e., from modelling, design, analysis, configuration, and execution on the hardware platform. TSN is still a hot research topic and the results achieved in this project extended the state of the art on this topic. The project attempted to promote research, innovation capacity, and competence in the Swedish vehicle industry by addressing the listed scientific challenges. The project results are achieved with the help of a strong academic-industrial collaboration, thereby promoting university-industry cooperation. The project also promoted the participation of one SME (Arcticus Systems) and one large-sized enterprise (Volvo CE). The results of the projects have been disseminated to national and international forums, allowing wider visibility of the project outcomes. Table 1 shows the level of contribution to the three overall objectives of FFI in the theme of “Climate and Environment” and “security”.

Table 1. Contribution to overall FFI objectives (the text is taken from FFI programme description).

Overall for FFI, in the theme areas Climate & Environment and Safety	**Level**	**Motivation**
Protecting the Swedish automotive industry's competitiveness and jobs in the long term — and preferably also in the short term — through increased research and innovation capacity.	High	The successful adoption of novel high-performance and high-safety communications standards like TSN is imperative for the sustained industrial competitiveness. DESTINE attempted to make this novel technology more usable by providing support for development of next-generation vehicle functions based on high data-rate sensor and computations.

The development of internationally connected and competitive research and innovation environments in which, among others, academia, research institutes and industry work hand in hand.	High	The main applicant, MDU, is firmly grounded in the international research community. The project team are top researches in fields like embedded communication, embedded-software development and use of reconfigurable hardware in embedded applications. Furthermore, the three project partners have an outstanding track record of co-producing academic research of the highest standard (10+ joint projects and 50+ joint publications). We also shared and refined the project results with broader Swedish and European industry via sharing results using other projects participated by the project members and by organizing 5 editions of Workshop on Advanced Technologies in Vehicular Systems (DIVERSE) at the international conference on Emerging Technologies and Factory Automation (ETFA) 2019-2024.
Promoting international research and innovation activities, for which the conditions for and participation in EU framework programs (as well as other international research and innovation collaboration) are carefully evaluated.	High	The project partners have a strong track record in combining their industrial and academic networks to form competitive international consortia to target international funding in schemes like H2020, ITEA and ECSEL. Using the project's platform, we have already formed a European consortium and are planning to apply for EU funding in the future.

The outcomes of DESTINE contribute to the main objectives of Electronics, software and communication (EMK) FFI sub-programme within the area of electrical architecture in the vehicle (Elarkitektur-inom fordonet). The most significant contribution of DESTINE is the development and execution support for onboard communication with high-bandwidth and low-latency real-time transmission of high data-volumes in vehicles by employing the IEEE Ethernet TSN standards. As TSN supports various criticality levels of traffic, the mixed-criticality feature is supported by design. Moreover, the project results facilitate the use of nodes with high computational power (sensors, actuators, and ECUs) in vehicles. Table 6 provides justification of the project contributions to the sub-programme roadmap.

Table 6. Justification of relevance to the sub-programme (grey boxes are taken for programme description).

Electrical architecture within the vehicle (*Elarkitektur-inom fordonet*)		
Onboard communication (*Intern kommunikation*)	Long term: Significantly higher bandwidth requirements with high reliability and energy efficiency.	TSN supports high bandwidth communication with various classes of traffic, from hard-real-time to non-real-time traffic. DESTINE leverages these features to support development of safe, reliable and high-performing functions.
Mixed-criticality (*Blandad kritikalitet*)	Short term: Architecture concept to protect security-critical functionality onboard from other features.	TSN natively supports multiple, separated, classes of traffic with possibility of reserving resources for each. In DESTINE we take a system perspective on optimising the use of the network resource, taking vehicular constraints as safety, reliability and throughput into account.
Computation power (Beräkningskraft)	Mid-term: Manage increased computation requirements from new demanding applications as an integral part of the electrical architecture.	The high, and predictable, data-rates offered by TSN pave way for the envisioned functions with large demand on computational-power. The results of DESTINE support configuration and optimization of the network, which is non-trivial.
Sensor data (sensor data)	Mid-term: Manage great amount of required sensor data to handle high-level automation applications.	Data-intensive sensors in modern vehicles, especially in autonomous vehicles, require high-bandwidth low-latency communication to transmit the heavy real-time data to the computation nodes (ECUs). This support can be only obtained by an efficient configuration of backbone TSN network, which is one of the main results of DESTINE.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The project results provide new knowledge that extends state of the art in model-based software development, schedulability analysis and resource optimization of real-time networks in the embedded systems domain in general and in the vehicular domain in particular.
Be passed on to other advanced technological development projects	X	The research community and the industry has been showing great interest in TSN for the past 5 years. This is due to many promising features of TSN that meet the industrial needs and standardization of TSN. The project results provide input to new and existing technological development projects that aim at developing applications with high-bandwidth low-latency real-time communication, e.g., PROVIDENT, INTERCONNECT funded by VINNOVA, and DPAC, SEINE and RELIANT funded by KKS.
Be passed on to product development projects	X	The project results are generally applicable to any industrial settings that require high-bandwidth and low-latency real-time communication. Using industrial seminars and trainings on TSN, workshops, and other industrial collaboration projects, we have already shared the project results with several other industrial players like Ericsson, ABB, HIAB, VGTT, Westermo, TCN, Thales. Some of these enterprises have already started to investigate the feasibility of the project results within their industrial setting. Such an investigation often starts with a feasibility or a pilot project. We believe, the project results would be passed on to such projects.
Introduced on the market	X	The newly developed techniques and frameworks are already implemented in a commercial tool chain (Rubus-ICE). This tool chain has been used by many international companies in the vehicle domain for over 25 years, including Volvo (party in DESITNE) and BAE systems. The final demonstrator on the use case by Volvo CE provided a demonstration for usability of the tool chain in the industrial settings. Note that the project results are not specific to one vehicle manufacturer. The other companies are also expected to benefit from the extended tool chain. Already today, HIAB, Ericsson and ABB are using the project results as a background in other research projects like PROVIDENT, INTERCONNECT, AORTA funded by VINNOVA, and DPAC, SEINE and RELIANT funded by KKS.
Used in investigations / regulatory / licensing / political decisions		

The project results have been disseminated to the scientific community via 35 publications (1 PhD thesis, 1 Licentiate thesis, 9 journals, 2 Guest Editorials, 22 conference). In addition, the project developed 4 tool prototypes and 1 industrial use-case demonstrator. The project results have been disseminated to a broader audience, **beyond the scientific publications.** We have organized five editions of an international Workshop on Advanced Technologies in Vehicular Systems (DIVERSE) on the project's theme. All editions of the workshop were located at the international conference on Emerging Technologies and Factory Automation (ETFA) 2019-2024 respectively. The workshop featured invited presenters from academia and industry in the vehicular domain. Using industrial seminars and trainings on TSN, workshops, and other industrial collaboration projects, we have already shared the project results with the industry both within Sweden and abroad, e.g., Ericsson, ABB, HIAB, VGTT, Westermo, TCN, Thales, to mention a few.

7.2 Publications

The project results have been disseminated to the scientific community in 35 publications as follows

- 1 PhD thesis
- 1 Licentiate thesis
- 9 journal articles
- 2 Guest Editorials in international journals
- 22 conference papers

Some of these publications [J5, J11] include sceintific reviews together with our findings on industrial requirements and worst-case scenarios as well as the results obtained during the project in state-of-the-art publications in high-ranked international journals. Furthermore, we coordinated the publication of two editorials [GE1, GE2] in international journals focusing on the project's theme.

Dissertations (2)

[J1] B. Houtan, "Configuration and Timing Analysis of TSN- based Distributed Embedded Systems", *Doctoral Thesis*, Mälardalen University, March 2024. http://www.es.mdu.se/publications/6897-

[J2] B. Houtan, "Configuring and Analysing TSN Networks Considering Low-priority Traffic", *Licentiate Thesis*, Mälardalen University, December 2021. http://www.es.mdu.se/publications/6897-

Journal Articles (9)

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8. Conclusions and future research

The IEEE Time-Sensitive Networking (TSN) task group developed a set of standards that run over the switched Ethernet to support high-bandwidth land ow-latency onboard real-time communication. Prior to this project, a complete development environment that supports modelling, timing analysis, configuration, simulation, and execution for vehicular applications that use TSN was missing from the state of the art. Leveraging TSN's complex features presents formidable challenges in developing intricate vehicle functions. The DESTINE project addressed these challenges by developing innovative techniques, methods, and prototypes to provide a full-fledged development environment for vehicular applications that use TSN as the communication backbone. In this context, the project facilitated modelling, timing and resource analysis, simulation, configuration, optimisation, and execution of end-to-end behaviour of complex distributed software functions deployed over TSN backbone. The project results were validated and their industry usability demonstrated through two key approaches: (i) implementing and applying newly developed scientific techniques and tool prototypes to a unified use-case demonstrator in the automotive industry, and (ii) creating a methodology and guidelines for end-users (such as application developers in the vehicle industry) to efficiently utilize the project results by designing TSN-based vehicular applications, taking into account resource utilization, legacy network protocols, and traffic properties.

The project consortium established an efficient value chain: from MDU (academia) developing new scientific techniques, to Arcticus (tool developer/vendor) implementing these techniques as tool prototypes, to Volvo CE (end user) applying the tools and new development methods in their industrial use case, and back-propagation of the feedback on usability for their refinement. The project results were disseminated to the scientific community via 35 publications (1 PhD thesis, 1 Licentiate thesis, 9 journals, 2 Guest Editorials, 22 conference). In addition, the project developed 4 tool prototypes and 1 industrial use-case demonstrator. The project results have been disseminated to a broader audience, beyond scientific publications. We have organized five editions of an international Workshop on Advanced Technologies in Vehicular Systems (DIVERSE) on the project's theme. The workshop featured invited presenters from academia and industry in the vehicular domain. Using industrial seminars and trainings on TSN, workshops, and other industrial collaboration projects. We have already shared the project results with the industry both within Sweden and abroad.

The future work entails broadening the scope of the project results by seamlessly integrating TSN with other legacy onboard communication protocols like Controller Area Network (CAN) and its various generations including the CAN-FD and CAN XL. Similarly, integration of TSN with high-bandwidth and low-latency wired communication protocols like 5G/6G will further broaden the scope of DESTINE's results to vehicular systems of systems. Another interesting and challenging future work is supporting automatic configuration and self-configuration of industrial networks in the case of faults and security threats. The scope of DESTINE was from TRL2-TRL5. The DESTINE project covered Technology Readiness Levels (TRLs) 2 to 5. In the future, our intention is to enhance and broaden the project outcomes to align with higher TRL levels.

9. Participating parties and contact persons

There are three participating parties in this project. Each party with its contact person is listed below.

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