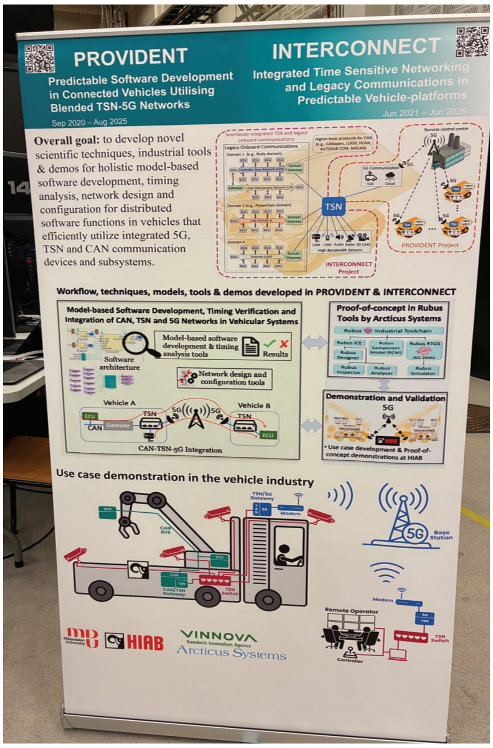
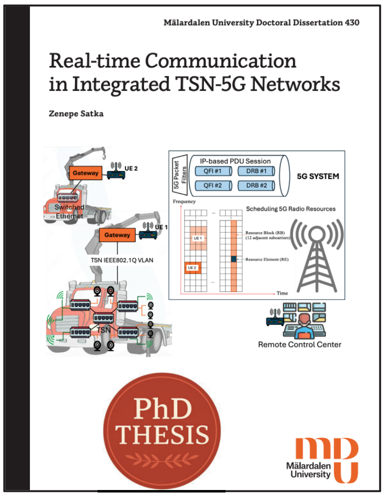
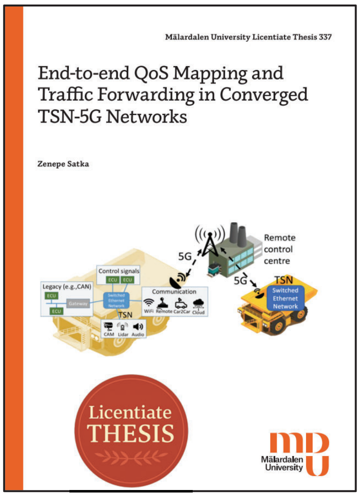
PROVIDENT: Predictable Software Development in Connected Vehicles Utilising Blended TSN-5G Networks

Public report







Project within FFI- Elektronik, mjukvara och kommunikation
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Date 2025.12.31

FFI Fordonsstrategisk Forskning och Innovation

PROVIDENT TSN-5G

Content

1. **Summary** 3
2. **Sammanfattning på svenska** 4
3. **Background** 6
4. **Purpose, research questions and method** 7
   - 4.1 Research challenges 8
   - 4.2 Scientific method 9
5. **Objective** 9
6. **Results and deliverables** 10
   - 6.1 Deliverables and goals fulfilment 10
   - 6.2 Relevance to the programme objectives 12
7. **Dissemination and publications** 15
   - 7.1 Dissemination 15
   - 7.2 Publications 17
8. **Conclusions and future research** 20
9. **Participating parties and contact persons** 22

References 22

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

For more information: www.vinnova.se/ffi

1. Summary

Modern vehicles in many segments of the vehicular domain need to communicate, coordinate and collaborate to achieve a joint functionality, in e.g., an autonomous quarry, recycling site, forest or a mine. To provide such functionality, these vehicles need to be equipped with numerous high data-rate sensors (e.g., cameras, radars, and lidars) that can generate hundreds of megabytes of data per second. Furthermore, the large amount of data acquired from these sensors needs to be communicated with predictable and low latencies between the computing units within the vehicles (microseconds to milliseconds range) as well as among the vehicles and their control centre (milliseconds range). The traditional intra-vehicle communication (based on field buses and primitive Ethernet solutions) and inter-vehicle communication (based on wireless solutions like WiFi and 4G) are bottlenecks in meeting the high-bandwidth and low-latency communication requirements. The IEEE Time-Sensitive Networking (TSN) and 5G standards offer promising solutions to address the communication requirements within and among the vehicles respectively. However, the research on the software development for predictable vehicular systems that utilize TSN and 5G was still in its infancy in the start of this project.

This project envisioned the novel possibility of blended TSN-5G communication to be a viable solution in meeting the communication requirements for these coordinated vehicles. However, the state of the art lacked a holistic software development framework and execution environment for predictable vehicular systems that utilize blended TSN-5G communication. This lack of knowledge base hindered the industry from taking full advantage of these ground-breaking technologies in developing highly cost-effective, efficient and reliable vehicles. The PROVIDENT project aimed to develop novel techniques and frameworks to provide a full-fledged holistic software development environment for connected collaborating vehicles that utilize blended TSN-5G communication.

The project results support software modelling, timing verification, deployment and execution of complex software functionality in these vehicles. The project also developed an integrated demonstrator prototype to validate the project results on a use case in the industrial settings of HIAB. The use case consisted of a truck-mounted crane, where the teleoperation of the crane was realized by integrating 5G and TSN to provide a seamless end-to-end communication across the system. These results bring several benefits to the vehicle industry, including cost-efficient system development, better quality of developed functions to lower costs, better use of expensive and scarce communication resources, and ease to demonstrate timing predictability verification and high degree of automation in the development process.

The project consortium consisted of three partners, including the project coordinator Mälardalen University (MDH), Arcticus Systems and HIAB. The project developed proof-of-concept prototypes of these techniques by extending the Rubus models and tools (provided by Arcticus), which have been used in the vehicle industry for over 25 years. A major benefit of this team is that it offered a clear value chain from development of new

techniques in academia (MDH); through their implementation in industrial tools by a tool developer (Arcticus Systems); to their utilisation by an end user of the technology in the vehicle industry (HIAB); and back-propagation of the feedback on usability for the refinement of the developed techniques and prototypes.

Overall, the project results were encapsulated in 35 publications (1 PhD thesis, 1 Licentiate thesis, 7 journal articles, 2 Guest Editorials, 24 conference papers). Some of these publications include scientific 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 a tool prototype and an 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) 2021-2025 respectively. The workshop featured invited presenters from academia and industry in the vehicular domain, including presentations by our industrial partners Arcticus Systems and HIAB as well as by Volvo CE (project's reference group member). 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., Volvo CE, Ericsson, ABB, Westermo, TCN, Bosch, Thales, to mention a few.

2. Sammanfattning på svenska

Moderna fordon inom många segment av fordonsdomänen behöver kommunicera, samordna och samarbeta för att uppnå gemensamma funktioner, till exempel i en autonom gruva, återvinningsplats, skog eller ett stenbrott. För att möjliggöra sådan funktionalitet måste dessa fordon vara utrustade med ett stort antal sensorer med hög datahastighet (t.ex. kameror, radar och lidar) som kan generera hundratals megabyte data per sekund. Dessutom måste den stora mängd data som samlas in från dessa sensorer överföras med förutsägbara och låga latenser mellan beräkningsenheterna i fordonen (mikrosekunder till millisekunder) samt mellan fordonen och deras kontrollcenter (millisekunder). Traditionell kommunikation inom fordon (baserad på fältbussar och primitiva Ethernet-lösningar) och mellan fordon (baserad på trådlösa lösningar som WiFi och 4G) utgör flaskhalsar för att uppfylla kraven på hög bandbredd och låg latens. IEEE Time-Sensitive Networking (TSN) och 5G-standarderna erbjuder lovande lösningar för att möta kommunikationskraven inom respektive mellan fordon. Vid projektets start var dock forskningen kring mjukvaruutveckling för förutsägbara fordonsystem som använder TSN och 5G fortfarande i sin linda.

Detta projekt förutsåg den nya möjligheten att integrerad TSN-5G-kommunikation skulle kunna vara en livskraftig lösning för att uppfylla kommunikationskraven för dessa samordnade fordon. Dock saknades det i den aktuella kunskapsnivån en heltäckande mjukvaruutvecklingsram och exekveringsmiljö för förutsägbara fordonsystem som använder integrerad TSN-5G-kommunikation. Denna kunskapsbrist hindrade industrin från att fullt ut dra nytta av dessa banbrytande teknologier för att utveckla kostnadseffektiva, effektiva och tillförlitliga fordon. PROVIDENT-projektet syftade till att utveckla nya tekniker och ramverk för att tillhandahålla en komplett mjukvaruutvecklingsmiljö för uppkopplade och samarbetande fordon som använder integrerad TSN-5G-kommunikation.

Projektresultaten stödjer mjukvarumodellering, tidsverifiering, distribution och exekvering av komplex mjukvarufunktionalitet i dessa fordon. Projektet utvecklade också en integrerad demonstratorprototyp för att validera projektresultaten i ett industriellt användningsfall hos HIAB. Användningsfallet bestod av en lastbilskran där fjärrstyrning av kranen realiserades genom att integrera 5G och TSN för att möjliggöra sömlös end-to-end-kommunikation i systemet. Dessa resultat ger flera fördelar för fordonsindustrin, inklusive kostnadseffektiv systemutveckling, bättre kvalitet på utvecklade funktioner för att sänka kostnader, bättre utnyttjande av dyra och begränsade kommunikationsresurser samt enkelhet att demonstrera tidsförutsägbarhet och hög grad av automatisering i utvecklingsprocessen.

Projektkonsortiet bestod av tre partners: projektkoordinatorn Mälardalens universitet (MDH), Arcticus Systems och HIAB. Projektet utvecklade proof-of-concept-prototyper av dessa tekniker genom att utöka Rubus-modeller och verktyg (tillhandahållna av Arcticus), som har använts i fordonsindustrin i över 25 år. En stor fördel med detta team är att det erbjöd en tydlig värdekedja från utveckling av nya tekniker inom akademin (MDH), via implementering i industriella verktyg av en verktygsutvecklare (Arcticus), till användning av teknologin hos en slutanvändare i fordonsindustrin (HIAB), samt återkoppling av användbarhetsfeedback för att förfina de utvecklade teknikerna och prototyperna.

Sammanfattningsvis har projektresultaten sammanställts i 35 publikationer (1 doktorsavhandling, 1 licentiatavhandling, 7 tidskriftsartiklar, 2 gästeditorialer, 24 konferensartiklar). Några av dessa publikationer innehåller vetenskapliga översikter tillsammans med våra resultat om industriella krav och worst-case-scenarier samt de resultat som erhölls under projektet i state-of-the-art-publikationer i högt rankade internationella tidskrifter. Dessutom koordinerade vi publiceringen av två editorialer i internationella tidskrifter med fokus på projektets tema. Projektet utvecklade också en verktygsprototyp och en industriell demonstrator. Projektresultaten har spridits till en bredare publik, utöver de vetenskapliga publikationerna. Vi har organiserat fem upplagor av den internationella workshopen om avancerade teknologier i fordonsystem (DIVERSE) med projektets tema. Alla upplagor av workshopen hölls vid den internationella konferensen Emerging Technologies and Factory Automation (ETFA) 2021–2025. Workshopen innehöll inbjudna talare från akademi och industri inom fordonsområdet, inklusive presentationer av våra industripartners Arcticus Systems och HIAB samt av Volvo CE (medlem i projektets referensgrupp). Genom industriseminarier och utbildningar om TSN, workshops och andra industriella samarbetsprojekt har vi redan delat projektresultaten med industrin både i Sverige och internationellt, t.ex. Volvo CE, Ericsson, ABB, Westermo, TCN, Bosch, Thales, för att nämna några.

3. Background

Vehicle industry is strategically important for Sweden's economy. One key indicator is the volume of exports linked to road vehicles, which was worth 214 billion SEK (in 2018) that comprised approximately 10% of all of Sweden's export products [1]. It is estimated that more than 80% of innovation in vehicles comes from the software that runs on the onboard computers, also known as the Electronic Control Units (ECUs) [2]. Modern vehicles in many segments of the vehicular domain, such as construction vehicles, loading trucks, recycling cranes, mining vehicles, etc. often need to communicate, collaborate and coordinate with each other and with their control centre to achieve a common goal or a joint functionality of the vehicular system of systems, e.g., an autonomous quarry. To provide such functionality, these vehicles require high computational power to process large amount of data acquired from high data-rate sensors (e.g., video cameras and lidars can generate hundreds of megabytes of data per second). Moreover, to meet the timing predictability[1] requirements on the internal functionality of each vehicle and on the joint functionality of collaborating vehicles, it is required to communicate the large amount of data among the ECUs via high-bandwidth and low-latency predictable networks within each vehicle as well as among the vehicles and their control centre.

None of the existing in-vehicle networks supported high-bandwidth and low-latency in-vehicle communication until when the IEEE Time-Sensitive Networking (TSN) task group [7]-**Error! Reference source not found.** developed a set of standards that utilise switched E thernet. The architectures based on the TSN standards have become promising solutions for high-bandwidth and low-latency onboard communication in various domains due to several novel features, including the support for different classes of real-time traffic, time-triggered traffic, best-effort traffic, resource reservations for various traffic, clock synchronization, and traffic shaping. The support for high-bandwidth and low-latency predictable wireless communication among the vehicles and the control centre was also missing until the recent introduction of 5G communication. 5G can support up to 100 times faster speeds than 4G and can guarantee down to 1 millisecond network latency [10],[11], which is a promising solution for connected vehicles in coordinated sites such as autonomous quarries. **Our vision** is that a blend of TSN and 5G communication (i.e., TSN within vehicles and 5G among the vehicles and their control centre) is a viable solution to meet the requirement of high-bandwidth and low-latency holistic network communication in collaborating connected vehicles as shown in Figure 1.

Prior to the initiation of this project, there was a wealth of existing research [2],[4]-**Error! R eference source not found.**,[12],[13] that aimed at providing software development techniques for predictable vehicular systems that are deployed on powerful ECUs (e.g., multi-core processors), which are connected by traditional low-bandwidth and low-latency or high-bandwidth and high-latency networks. However, the research on the software development for predictable vehicular systems that utilise TSN or 5G was still in its infancy

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[1]A system or a network is said to be timing predictable if it is possible to prove or demonstrate before running the system/network that all the specified timing requirements are satisfied [3].

[2], e.g., the first and only software modelling technique for TSN was developed in the DESTINE project [14],[15] prior to the start of PROVIDENT. The state of the art lacked a holistic software development framework and execution environment for predictable vehicular systems that utilise a blend of TSN and 5G networks. This lack of knowledge and corresponding tool support tend to hamper the utilisation of ground-breaking technologies like TSN and 5G in the vehicle industry. The model-based software development framework developed in PROVIDENT consists of new holistic techniques for the software architecture modelling, timing predictability verification, and efficiently designing and integrating vehicular systems that utilise blended TSN-5G communication. This framework is accompanied by a tool chain that implements the techniques and a proof-of-concept validator to demonstrate its usability in the vehicle industry.

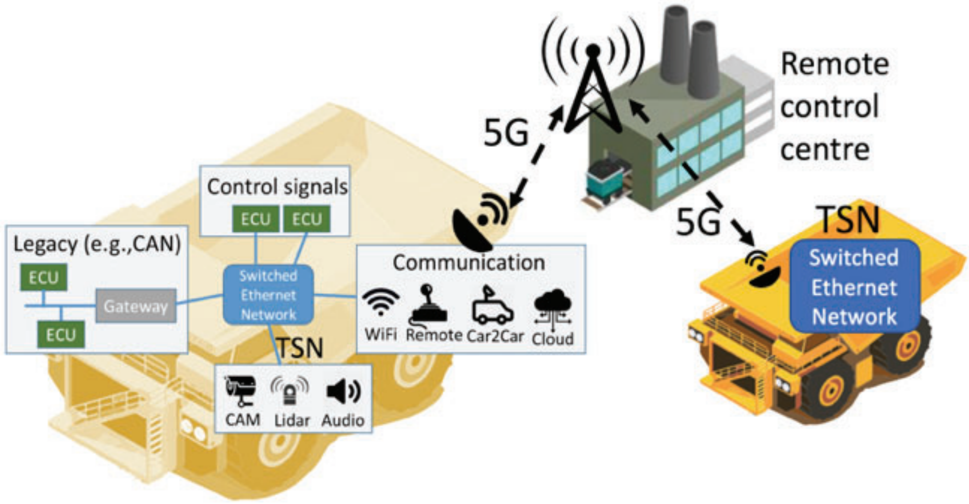

Figure 1: Conceptual view of PROVIDENT— collaborating vehicles utilizing blended TSN-5G networks.

4. Purpose, research questions and method

In this project, we envisioned the development of a model-based software development framework consisting of new holistic techniques for the software architecture modelling, timing predictability verification, and efficiently designing and integrating vehicular systems that utilise integrated TSN-5G communication. To showcase the practicality of these techniques in real-world settings, we developed a prototype of an industrial tool chain and provided an industrial use case demonstration on truck-mounted crane. In this use case, the teleoperation of the crane was realized by integrating 5G and TSN to provide a seamless end-to-end communication across the system. The envisioned workflow in PROVIDENT and the aimed scientific techniques, frameworks, prototypes and demonstrators are shown in Figure 2.

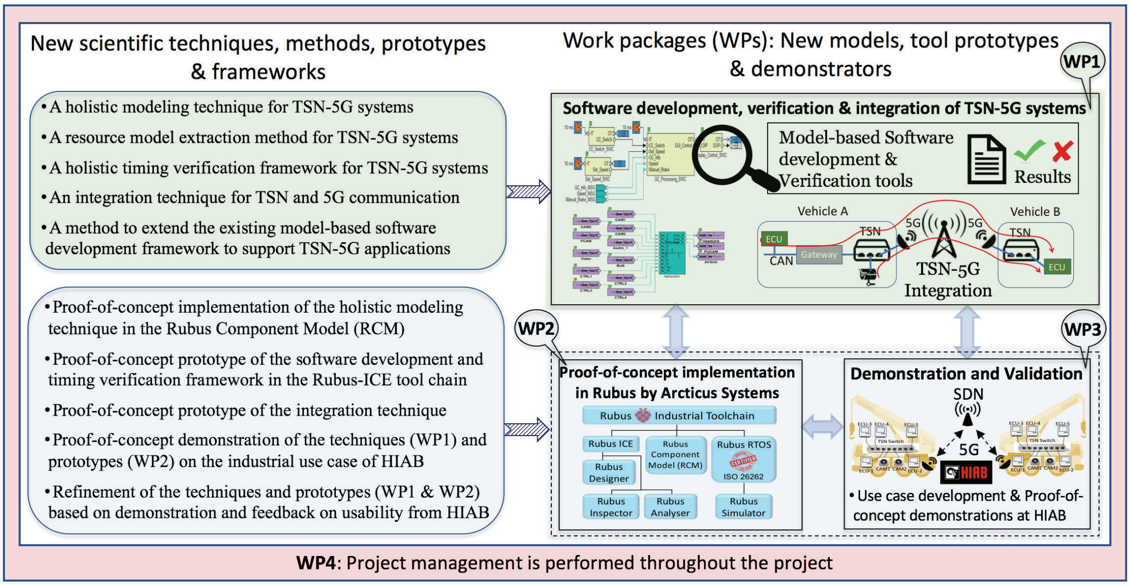

Figure 2: Workflow in the PROVIDENT project. Newly developed scientific techniques and frameworks are depicted on the left. New tools, prototypes and validators are shown on the right.

4.1 Research challenges

There are three key Research Challenges (RCs) that are addressed in achieving the project goals.

RC1: The first research challenge is how to develop a new holistic modelling technique for integrated TSN-5G communication that can be incorporated into the state-of-the-art model- and component-based software development frameworks in the vehicle domain. The technique is targeted to be expressive enough to model/extract resource information on/from the vehicular software architectures, including various QoS attributes, e.g., communication bandwidth and holistic timing properties.

RC2: The second research challenge is how to develop a new holistic timing predictability verification technique for vehicular systems that utilise a blend of TSN-5G communication, while considering different variations in the TSN and 5G standards. The technique is targeted to be integrated into the state-of-the-art holistic timing analysis framework for distributed vehicular applications.

RC3: Given the techniques developed in responses to RC1 and RC2, how to develop a methodology to efficiently integrate TSN-5G based vehicular systems with a clear view on holistic communication latencies, while considering legacy network protocols and traffic properties.

4.2 Scientific method

Given the project goal and expected outcomes (frameworks, techniques and proof-of-concept prototypes), the well-known research methodology of Systems Development [17] suited the most to this project. Using this methodology, first, we constructed a conceptual framework based on the core research challenges targeted in the project and relevant state-of-the-art literature. This step generated new ideas, concepts, theories, models and techniques. The system's requirements, assumptions, architecture, functionalities, relationship, and interactions among the system components were defined in the second step. Thereafter, the system was designed and analyzed in the third step. The studied domain knowledge was applied to develop alternative solutions. After evaluating these solutions against the requirements, the best performing solution was selected to develop, experiment, analyze and evaluate one or more prototypes of the system. In the case when the outcome of any step was not satisfactory, the methodology allowed us to go back to any previous step to perform the desired changes or optimizations. The whole process was iterated until the desired outcomes were achieved. The results and experiences from this methodology can be generalized and used to develop similar systems. Although this method is almost 30 years old, it works well in today's projects that require development of innovative frameworks, techniques and methods, especially in the embedded systems domain. We have also previously employed this method successfully in several research and technology transfer projects [16].

5. Objective

The overall goal of the project is: *to develop new techniques, methods, frameworks and tools to provide a full-fledged holistic software development, deployment and execution environment for vehicular systems that utilise a blend of TSN-5G networks for predictable communication, i.e., TSN as the backbone network within vehicles and 5G among the vehicles and their control centre* as shown in Fig. 2.

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

G_1: Develop a new holistic software modelling technique for vehicular systems that utilise a blend of TSN-5G communication.

G_2: Develop a new holistic timing predictability verification technique for vehicular systems that utilise a blend of TSN-5G communication.

G_3: Develop a new integration technique for TSN-5G communication in vehicular systems.

G_4: Develop a method to integrate all of the above techniques to the state-of-the-art model-based software development frameworks for vehicular systems.

G_5: Provide a proof-of-concept for the newly developed techniques and frameworks in an existing industrial tool chain, namely Rubus [16]. Develop prototypes in the industrial settings by modelling, analysing, deploying and executing vehicular systems on ECUs that are connected by a blended TSN-5G network.

6. Results and deliverables

The project results construct new knowledge and extend state of the art in the areas of model-based software development and schedulability analysis of real-time embedded systems in general and in the vehicle domain in particular. The scientific results in PROVIDENT are shown as the new scientific techniques, methods and frameworks on the left side of Figure 2. The project results are expected to have a considerable impact on the state of the practice in the vehicle domain with regards to new industrial tools, development models, prototypes and demonstrators are shown on the right side of Figure 2. Given these new techniques and tools, the results also include a methodology to guide the vehicle application designer to develop integrated TSN-5G 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 15 deliverables: 1 journal article, 8 conference/workshop papers, 2 internal technical report, 2 prototypes/demos, 1 integrated demo, and 1 Licentiate thesis. The project achieved significantly higher number of contributions in this regard. This is evident from the fact that the project results include 38 deliverables: 35 publications (1 PhD thesis, 1 Licentiate thesis, 7 journal articles, 2 Guest Editorials, 24 conference), 1 tool prototype, 1 tool chain prototype, and 1 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: We have addressed G_1 and RC1 by first completing the state-of-the-art review of modelling techniques that can be reused, adapted or extended to support holistic modelling of blended TSN-5G communication in vehicular systems [J3, J6, C19]. Learning from the above, we developed a software architecture modeling technique for 5G [C8]. Furthermore, we developed a novel frame preemption model for TSN [J7]. In order to facilitate the end-to-end modelling of TSN-5G communication, we developed a translation technique between TSN and 5G [C13] and a novel QoS mapping algorithm for TSN-5G systems [C12].

The second goal, G_2, and second research challenge, RC_2: We have addressed G_2 and RC2 by (i) completing the state-of-the- art review of timing analyses for holistic timing predictability verification of blended TSN-5G communication [J3, J6], (ii) developing a systematic method to extract end-to-end timing models from TSN-based systems [C10, C16], (iii) developing timing predictability verification framework for TSN-based vehicular distributed systems [C2, C3, C5, C20, C24], and (iv) end-to-end data-propagation delay analysis of TSN-based distributed systems [J4].

The third goal, G_3, and third research challenge, RC_3: We have addressed G_3 and RC3 by developing integration techniques for TSN and 5G networks. Moreover, we developed a methodology to efficiently integrate TSN-5G based vehicular systems with a clear view on holistic communication latencies, while considering legacy network protocols and traffic properties. In this context, we first performing experimental evaluation of integrated TSN-4G systems to set a baseline [C7]. Then we analysed implications of various pre-emption configurations in TSN networks [J5, J7]. We developed scheduling and configuration techniques for TSN networks [C17, C18, C21, C22] while integration techniques for TSN and legacy systems were developed in [J2, C15, C23]. Furthermore, we developed centralized configuration techniques for TSN networks as well as for TSN-5G networks [C6, C9, C11, C14]. Finally, we developed real-time scheduling techniques for integrated TSN and 5G communication in [C1], while integration techniques for TSN and 5G networks were developed in [C4, J1].

The fourth goal G_4: We addressed G_4 by integrating the modelling and analysis techniques (developed in response to G_1-G_3) to a state-of-the-art model-based software development framework [C2, C8, C10, C16, C20, J4].

The fifth goal G_5: We addressed G_5 by implementing the modelling and analysis techniques (developed in response to G_1-G_3) as prototypes of an industrial tool chain (Rubus-ICE) [C2, C8, C10, C16, C20, J4]. Furthermore, the techniques and tool prototypes were validated on an industrial use case of a truck-mounted crane. A conceptual view of the use case is depicted in Figure 3. In this use case, the teleoperation of the crane was realized by integrating 5G and TSN to provide a seamless end-to-end communication across the system.

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, J6]. Furthermore, we coordinated the publication of two editorials in international journals focusing on the project's theme [GE1, GE2].

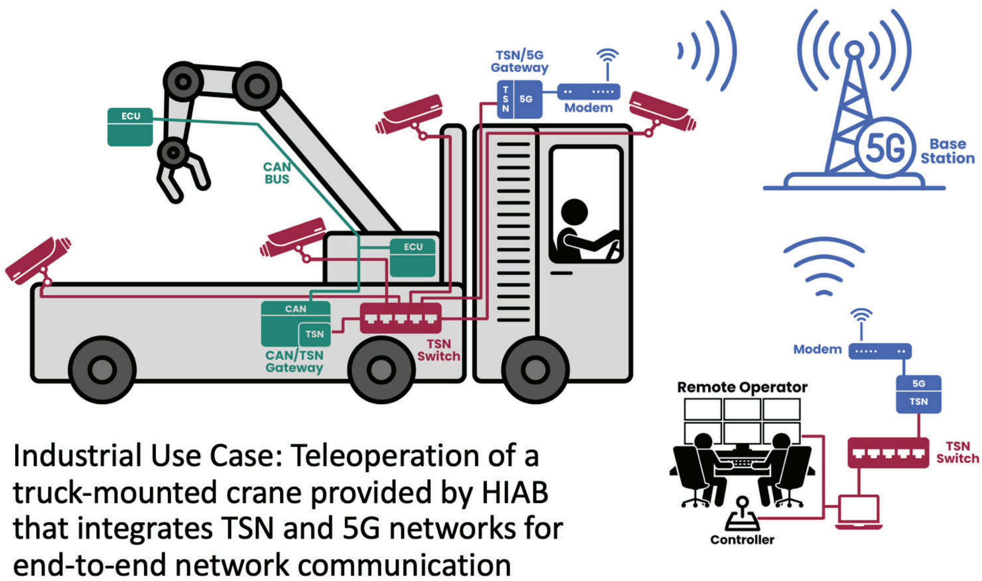

Figure 3: PROVIDNET's industrial use case demonstration.

6.2 Relevance to the programme objectives

The vehicle industry is striving for zero accidents, zero downtime, zero emissions, high automation, and full control over complete site operations, e.g., in an autonomous quarry, a mine or a forest site. One fundamental requirement in achieving these targets is to equip the vehicles with numerous high data-rate sensors (e.g., regular video and time-of-flight cameras, radars, lidars, GPS, to mention a few). Moreover, the large amount of data acquired from these sensors need to be processed and communicated with low and predictable latencies among ECUs within the vehicles (microseconds to milliseconds range) as well as among the vehicles and the control centre (milliseconds range). The traditional low-bandwidth low-latency in-vehicle communication (based on field buses) and high-bandwidth high-latency wireless communication among vehicles are becoming a bottleneck in meeting these requirements. Hence, there is an urgent need for high-bandwidth and low-latency predictable communication both within each vehicle and among the vehicles and their control centre.

The release of the TSN and 5G standards has sparked a huge interest in their utilisation, not only in the Swedish vehicle industry but also by many international Original Equipment Manufacturers (OEMs). This is evident from their active participation in national and international conferences exclusively on these technologies. The main challenge faced by the OEMs in utilising a blend of TSN and 5G communication in their vehicular products is the lack of a full-fledged development environment and tool chain to support software architecture modelling, timing predictability verification, deployment and execution. Given the tool support, another challenge faced by the industry is the lack of design guidelines and strategies for developing these applications in an efficient, reliable and cost-effective way.

There is a market-driven urgent need in the vehicle industry to deploy high-bandwidth low-latency intra- and inter-vehicle communication to support advanced data-intensive functionalities, especially in the segment of autonomous collaborating vehicles, in e.g., an autonomous quarry. PROVIDENT focuses on multiple levels of vehicular application development, i.e., from modelling, design and analysis down to deployment and execution. TSN and 5G are still hot research, especially when merging these two technologies. At the start of the project, there was no software development framework and execution environment for vehicular applications that use blended TSN-5G communication. This project promotes research and innovation capacity in the Swedish vehicle industry by addressing the listed scientific challenges. The project results are achieved with the help of a strong academic-industry collaboration. The project promotes participation of one SME (Arcticus Systems) and one large-sized enterprise (HIAB). The project results have been disseminated to national and international forums, allowing wider visibility of the project. The project results are expected to promot research activities in the EU framework programs. Table 1 shows the level of contribution to the overall objectives of FFI.

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 and 5G is imperative for the sustained industrial competitiveness. PROVIDENT aims at making these novel technologies more usable by providing support for development of next-generation vehicle functions based on high data-rate sensors and computations in the context of remote vehicle operation. This project is a step forward in making a strong Swedish node for developing and utilizing ground-breaking and advanced technologies in the vehicle industry.
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, MDH, is firmly grounded in the international research community. The team members are international top researchers and one of the leaders in the fields like embedded software development real-time systems, real-time communication, and vehicular embedded systems. Please note that the main applicant is co-chairing the IEEE Industrial Electronics Society's committee on **In-vehicle Embedded Systems**. This platform and other academic networks of the team provided an opportunity to enhance the competitiveness of the project hosting research environment by connecting with international renowned researchers in the area. Moreover, the project team's vast experience of developing innovative techniques and transferring them to the industry through several technology-transfer projects **Error! Reference source not f ound.** provided a useful input in meeting this requirement.
Promoting international research and innovation activities, for which the conditions for and participation in EU framework programs (as	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.

well as other international research and innovation collaboration) are carefully evaluated.		

The outcomes of PROVIDENT 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 PROVIDENT is the development and execution support for holistic communication in remote-operated vehicles using IEEE Ethernet TSN standards and 5G. Table 2 provides justification of the project contributions to the sub-programme roadmap.

Table 2. Justification of relevance to the sub-programme (grey boxes are taken for programme description).

Architecture (Arkitektur)		
External communication (extern kommunikation)	**Long term:** Extremely low latency and very high reliability for V2X in autonomous driving.	PROVIDENT provides software development techniques and execution environment for the development of safe, reliable and high-performing software functionality in collaborating connected vehicles that utilise blended TSN-5G communication for high-bandwidth and low-latency predictable communication. PROVIDENT leverages the high-bandwidth and ultra-low latency features of 5G to enable a safe and reliable V2X communication among the collaborating vehicles that perform a joint mission or a functionality in, e.g., an autonomous quarry, recycling site or a mine.
Onboard communication (*Intern kommunikation*)	**Long term:** Significantly higher bandwidth requirements with high reliability and energy efficiency.	PROVIDENT leverages various features of TSN to provide high-bandwidth and low-latency onboard communication within each vehicle to enable predictable and reliable vehicle functions.
Computation power (Beräkningskraft)	**Mid-term:** Handle increased computation requirements from new demanding applications as add-on solutions to	The high data-rates offered by TSN and 5G pave way for the envisioned vehicular functionalities with high computation and communication requirements. PROVIDENT developes a model-based software development framework to develop software architectures of these functionalities. It also

	existing electrical architecture.	provides a design methodology for configuring the blended TSN-5G communication to efficiently develop these functionalities.
Mixed-criticality (*Blandad kritikalitet*)	**Short term:** Architecture concept to protect security-critical functionality onboard from other features.	TSN natively supports multiple classes of traffic with different priorities, preemption of ongoing transmission, and possibility of reserving resources (e.g., bandwidth) for each class. Utilising these features, PROVIDENT associates safety-critical functionality to the scheduled traffic (highest priority and ultra-low latency), other critical functionalities to the real-time traffic classes, and non-critical functionality to the best effort traffic. Hence, PROVIDENT supports the development and execution of vehicle software functionalities that can have different criticality levels specified on them (e.g., the Automotive Safety Integrity Levels (ASIL A-D).
System of system (System-av- system)	**Short term:** Architecture concept to protect security-critical functionality onboard from other features.	PROVIDENT considers the perspective of system-of-systems in optimising the use of network resources (in-vehicle and V2X) considering vehicular constraints such as safety, reliability, latency and throughput.

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	X	The research community and the industry has been showing great interest in the integration of TSN and 5G technologies for

development projects		the past few years. This is due to many promising features of these technologies that meet the industrial needs and standardization efforts. 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., INTERCONNECT, AORTA, and FLEXATION 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 based on predictable wired and wireless networks. Using industrial seminars and trainings, workshops, and other industrial collaboration projects, we have already shared the project results with several other industrial players like Volvo CE, Ericsson, ABB, HIAB, VGTT, Westermo, TCN, Bosch, 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 and BAE Systems. The final demonstrator on the use case by HIAB 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, Volvo CE, Ericsson, ABB, and Westermo are

		using the project results as a background in other research projects like INTERCONNECT, AORTA, FLEXATION 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, 7 journal articles, 2 Guest Editorials, 24 conference papers). In addition, the project developed a tool prototype and an 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) 2020-2025 respectively. The workshop featured invited presenters from academia and industry in the vehicular domain, including presentations by our industrial partners Arcticus Systems and HIAB. Using industrial seminars and trainings, workshops, and other industrial collaboration projects, we have already shared the project results with the industry both within Sweden and abroad, e.g., Volvo CE, Ericsson, ABB, Westermo, TCN, Bosch, 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
- 7 journal articles
- 2 Guest Editorials in international journals
- 24 conference papers

Some of these publications [J3, J6] 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)

[Th1] Zenepe Satka, "Real-time Communication in Integrated TSN-5G Networks", *Doctoral Thesis*, Mälardalen University Sweden, May 2025, https://mdh.diva-portal.org/smash/record.jsf?pid=diva2%3A1946735&dswid=-113.

[Th2] Zenepe Satka, “End-to-end QoS Mapping and Traffic Forwarding in Converged TSN-5G Networks”, *Licentiate Thesis*, Mälardalen University Sweden, April 2023, https://www.es.mdu.se/pdf_publications/6776.pdf.

Journal Articles (7)

[J1] Z. Satka, M. Ashjaei, J. Nord, W. Rosales Mayta, D. Nordin, D. Ragnarsson, and S. Mubeen, “Bridging TSN and 5G networks: Prototype design and evaluation for real-time embedded systems”, in *Journal of Systems Architecture*, vol. 168, 2025, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2025.103531.

[J2] D. Bujosa Mateu, J. Proenza, A. Papadopoulos, T. Nolte, M. Ashjaei, “TALESS: TSN with Legacy End-Stations Synchronization”, in *Open Journal of the Industrial Electronics Society*, vol. 5, 2024, doi: 10.1109/OJIES.2024.3436590.

[J3] Z. Satka, M. Ashjaei, H. Fotouhi, M. Daneshtalab, M. Sjödin, and S. Mubeen, “A comprehensive systematic review of integration of time sensitive networking and 5G communication”, *Journal of Systems Architecture*, vol. 138, 2023, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2023.102852.

[J4] B. Houtan, M. Ashjaei, M. Daneshtalab, M. Sjödin, S. Mubeen, “Supporting end-to-end data propagation delay analysis for TSN-based distributed vehicular embedded systems”, in *Journal of Systems Architecture*, vol. 141, 2023, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2023.102911.

[J5] M. Ashjaei, L. Murselović, S. Mubeen, "Implications of Various Preemption Configurations in TSN Networks," in *IEEE Embedded Systems Letters*, vol. 14, no. 1, pp. 39-42, 2022, doi: 10.1109/LES.2021.3103061.

[J6] M. Ashjaei, L. Lo Bello, M. Daneshtalab, G. Patti, S. Saponara, S. Mubeen, “Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities”, in *Journal of Systems Architecture*, vol. 117, 2021, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2021.102137.

[J7] M. Ashjaei, M. Sjödin, S. Mubeen, “A Novel Frame Preemption Model in TSN Networks”, in *Journal of Systems Architecture*, vol. 114, 2021, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2021.102037.

Guest Editorials (2)

[GE1] S. Mubeen, M. Ashjaei, M. Becker, “Guest Editorial: Special issue on Real-Time Distributed Computing”, in *Journal of Systems Architecture,* 2023, ISSN 1383-7621, https://www.sciencedirect.com/special-issue/10K8FP3CPSR

[GE2] S. Mubeen, L. Lo Bello, M. Daneshtalab, S. Saponara. “Guest Editorial: Special issue on parallel, distributed, and network-based processing in next-generation embedded systems”, in *Journal of Systems Architecture,* 2021, ISSN 1383-7621, https://doi.org/10.1016/j.sysarc.2021.102159

Conference Publications (24)

[C1] Z. Satka, F. Aromolo, M. Ashjaei, A. Biondi, D. Casini, H. Fotouhi, N. Borgiol, M. Daneshtalab, M. Sjödin, S. Mubeen, “Real-time Scheduling of 5G Radio Resources to Support Time Sensitive Networking Traffic”, Technical report, Mälardalen University, 2025. Under review in the 32nd IEEE Real-Time and Embedded Technology and Applications Symposium, 2026.

[C2] D. Bujosa Mateu, M. Ashjaei, S. Mubeen, "CONAN-TSN: An Integrated Toolchain for CONfiguration and ANalysis of TSN Networks" in the *30th IEEE International Conference on Emerging Technologies and Factory Automation*, 2025.
[C3] D. Bujosa Mateu, J. Proenza, A. Papadopoulos, T. Nolte, M. Ashjaei, "An Improved Worst-Case Response Time Analysis for AVB Traffic in Time-Sensitive Networks", in the *45th IEEE Real-Time Systems Symposium*, 2024.
[C4] Z. Satka, S. Mubeen, M. Ashjaei, D. Ragnarsson, D. Nordin "Enhancing Real-Time Networked Embedded Systems with End-to-end TSN-5G Networks", in the *14th IEEE International Symposium on Industrial Embedded Systems*, 2024.
[C5] B. Houtan, M. Ashjaei, M. Daneshtalab, M. Sjödin, S. Mubeen, "Bandwidth Reservation Analysis for Schedulability of AVB Traffic in TSN", in the *25th IEEE International Conference on Industrial Technology*, 2024.
[C6] I. Alvarez, S. Mubeen, M. Ashjaei, "Using NETCONF for Automatic Fault Diagnosis in Time-Sensitive Networking" in the *29th International Conference on Emerging Technologies and Factory Automation*, 2024.
[C7] Z. Satka, D. Barhia, S. Saud, S. Mubeen, M. Ashjaei, "Experimental Analysis of Wireless TSN Networks for Real-time Applications", in the *28th IEEE International Conference on Emerging Technologies and Factory Automation*, 2023.
[C8] Z. Satka, S. Mubeen, M. Ashjaei, J. Lundbäck, "Towards Modelling 5G Communication in Software Architectures of Vehicular CPS", in the *49th Euromicro Conference Series on Software Engineering and Advanced Applications*, 2023.
[C9] I. Alvarez, D. Bujosa Mateu, B. Johansson, M. Ashjaei, S. Mubeen, "Centralised Architecture for the Automatic Self-Configuration of Industrial Networks" in the *28th International Conference on Emerging Technologies and Factory Automation*, 2023.
[C10] B. Houtan, M. Onur Aybek , M. Ashjaei, M. Daneshtalab, M. Sjödin, J. Lundbäck, S. Mubeen, "End-to-end Timing Modeling and Analysis of TSN in Component-Based Vehicular Software", in the *25th IEEE International Symposium on Real Time Distributed Computing*, 2023.
[C11] Z. Satka, I. Alvarez, M. Ashjaei, S. Mubeen, "A Centralized Configuration Model for TSN-5G Networks", in the *27th IEEE International Conference on Emerging Technologies and Factory Automation*, 2022.
[C12] Z. Satka, M. Ashjaei, H. Fotouhi, M. Daneshtalab, M. Sjödin, S. Mubeen, "QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows", in the *28th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, 2022.
[C13] Z. Satka, D. Pantzar, A. Magnusson, M. Ashjaei, H. Fotouhi, M. Sjödin, M. Daneshtalab, S. Mubeen, "Developing a Translation Technique for Converged TSN-5G Communication", in the *18th IEEE International Conference on Factory Communication Systems*, 2022.
[C14] I. Alvarez, A. Servera, J. Proenza , M. Ashjaei, S. Mubeen , "Implementing a First CNC for Scheduling and Configuring TSN Networks", in the *27th IEEE International Conference on Emerging Technologies and Factory Automation*, 2022.
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8. Conclusions and future research

Modern vehicular systems require seamless communication within and across vehicles to enable advanced functionalities such as teleoperation of vehicles in industrial environments. Prior to this project, the state of the art lacked a development environment that could support end-to-end software architecture modeling, timing analysis, and end-to-end network configuration for vehicular applications utilizing blended TSN-5G communication. Combining TSN's deterministic features with 5G's wide-area connectivity introduces significant complexity in designing predictable and reliable vehicle functions. The PROVIDENT project addressed these challenges by developing novel techniques, frameworks, and tool prototypes to enable a holistic software development environment for collaborating vehicles using TSN and 5G as the communication backbone. In this context, the project facilitated modeling, scheduling, timing verification, and resource analysis of end-to-end behavior for complex distributed software functions over integrated TSN-5G networks. The project results were validated and their industrial applicability demonstrated through two key approaches: (i) implementing and applying newly developed scientific methods and tool prototypes to an industrial use-case demonstrator involving teleoperation of a truck-mounted crane using TSN and 5G for seamless end-to-end communication, and (ii) creating methodologies and guidelines for end-users, such as application developers in the vehicle industry, to efficiently design TSN-5G-based vehicular applications while considering resource utilization, legacy protocols, and traffic properties.

The project partners created a clear value chain. It starts with MDU (academia), where new scientific techniques and software development approaches are developed. These novel techniques and approaches are then taken up by Arcticus Systems, which implements them as prototypes for their industrial tool chain. Finally, HIAB, a vehicle manufacturer and end user of the technology, techniques and tools, applies them in their industrial use case: teleoperating a truck-mounted crane using integrated 5G and TSN technologies to ensure smooth, end-to-end communication across the system. Feedback from po on usability flows back through the chain, helping refine and improve the techniques and tools.

The project results were disseminated and widely shared with the scientific community through 35 publications, including 1 PhD thesis, 1 Licentiate thesis, 7 journal articles, 2 guest editorials, and 24 conference papers. Several of these publications combined scientific reviews with our findings on industrial requirements, worst-case scenarios, and project outcomes, published in leading international journals. We also coordinated two editorials in international journals that focused on the project's theme. Beyond publications, the project delivered a tool prototype and an industrial demonstrator. To reach a broader audience, we organized five editions of the international Workshop on Advanced Technologies in Vehicular Systems (DIVERSE), held annually from 2021 to 2025 at the international conference on Emerging Technologies and Factory Automation (ETFA). These workshops featured invited speakers from academia and industry, including regular presentations by our partners Arcticus Systems and HIAB as well as by Volvo CE (project's reference group member). Furthermore, we actively engaged with industry through seminars, training sessions, workshops, and collaborative projects. This allowed us to share results with companies in Sweden and internationally, such as Volvo CE, Ericsson, ABB, Westermo, TCN, and Bosch, Thales.

Future research will focus on expanding the project's scope by integrating blended TSN-5G networks with emerging communication protocols such as Controller Area Network eXtra Long (CANXL) and the next-generation wireless standard Wi-Fi 8. Another important and challenging direction is enabling automatic and self-configuration of TSN-5G networks to handle faults and respond to security threats effectively. The PROVIDENT project covered Technology Readiness Levels (s) 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.

1. Mälardalen University, Västerås, Sweden
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2. HIAB, Hudiksvall, Sweden
   - Contact person: Hans Lyngbäck, hans.lyngback@hiab.com

3. Arcticus Systems, Järfälla, Sweden
   - Contact person: John Lundbäck, john.lundback@arcticus-systems.com

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