University Politehnica Timișoara

System Engineering

Hardware-Software IIoT solutions for interoperating and improving Automotive systems in the context of Industry 4.0

PhD Thesis Summary

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CONTENT

1. INTRODUCTION

1.1. Domain of the Thesis

In recent years, the concepts of Industrial Internet of Things and Industry 4.0 have become increasingly present in both scientific research and industry. Both concepts are based on the interoperability of complex systems, specific to several industrial sectors, with the aim of improving current performances. The interaction of complex systems implies, from one industrial sector to another, a multitude of specialized hardware and software solutions for particular industrial processes with different technological needs and dependencies. Usually, traditional technologies used in large-scale industry have been designed with precise objectives and have been validated over time in scenarios based on the needs of an industrial sector. Therefore, adapting current solutions to broader use cases is challenging and the only feasible way to achieve it requires a series of development steps, from the architectural level to the actual implementation of the underlying mechanisms and their validation. In order to make this granular development process as efficient as possible, a first step should be to identify as accurately as possible the requirements and needs for future IIoT systems, and afterwards to select the technologies with the greatest potential and impact within the industrial sectors of major interest.

The automotive sector is currently one of the most developed industrial sectors and a key pillar of the global economy. The relationship between supply and demand is constantly facilitating production, and year after year, massive investment is being made in research and development, with the aim of continuous technological development. Taking into account recent developments, it can be said that the automotive sector is undergoing a transition towards mass production of electric and autonomous cars. This transition is stimulating the development of hardware and software technologies capable of sustaining the industry in the long term, and a new vision is emerging that expands the horizons explored so far. Taking into account the concepts of autonomous driving, as well as the expected evolution of architectures and interconnection and interoperation capabilities, it is the most opportune moment to put the automotive and IIoT sectors in a common context, following specific Industry 4.0 development principles. Considering that the term Internet of Things has a significant reach, the design of advanced interoperability solutions will require the combination of technologies with diverse capabilities, typically specific to industrial automation sectors, together with the most advanced automotive technologies.

The main concepts and technologies targeted are generally advanced Ethernet communication protocols, architectures that involve multiple hardware devices with varying capabilities, and communication paradigms that facilitate efficient and preferably real-time data distribution. For the development of automotive-IIoT solutions, efficiency, feasibility, scalability, and flexibility aspects should be pursued. Ethernet communication efficiency is at the core of the IoT concept and is certainly an area of research where significant advances with high industrial impact can be achieved.

In the research stages, the targeted technologies currently belong to clearly defined industrial sectors, but used in a common context, they offer new perspectives and precise results confirming the progress and proposed objectives. Considering the field of industrial automation, which can be undoubtedly perceived as a subcomponent of the IoT sector, the OPC UA (Open Platform Communications Unified Architecture) protocol has been used in numerous prototypes and original concepts, and its reach and popularity in both industrial and academic contexts is well known. Associated with the OPC UA protocol, investigations and experiments have been carried out on Time Sensitive Networking (TSN) technology and Posix operating systems, both of which are current topics of great interest in many industrial developments. The recognized and validated middleware solution for communication over Ethernet in the automotive industry is SOME/IP (Scalable Service-Oriented Middleware over IP). As the protocol used in most applications available today and part of the AUTOSAR (AUTomotive Open System ARchitecture) standard, SOME/IP has been selected as the reference technology during the various research stages, aiming for the highest possible authenticity with respect to the industry. In addition to technologies that can be unequivocally associated with particular industrial sectors, there are also technologies with great potential, consistent with both the automotive sector and the IoT domain, which are not necessarily placed and spread in a specific context. The Data Distribution

Service (DDS) protocol and the enhanced Communication Abstraction Layer (eCAL) middleware solution are in this category, and have been targeted in the implementations of the various research phases. In recent years, DDS has been continuously expanding and started to be categorized as an IoT protocol, being used in a wide variety of scenarios, offering also automotive compliance with the AUTOSAR standard. The eCAL middleware solution has become available more recently, is not widely known, and the areas of applicability are not yet established. However, eCAL has its technological origins in the automotive domain and represents an alternative to existing Ethernet communication solutions that is worth exploring in detail. The analysis of these technologies in various operating contexts, the improvement of the architectures, the related mechanisms and the exploration of the possibilities of real-time performance, outline the topic of the current thesis, aiming to obtain the most eloquent results in relation to all the mentioned aspects, and to develop concrete solutions that improve the efficiency of industrial processes, highlighting new capabilities needed in Industry 4.0 circumstances.

1.2. Objectives

The objectives of the current doctoral research are structured in line with industrial needs and major topics of interest in the academic community. Interoperability principles associated with Industry 4.0 and IIoT concepts are pursued, and the solutions developed contribute to the improvement of Ethernet communication systems and the refinement of complex architectures. The developed concepts are applied in a diverse context, following at each stage of the research the association with sophisticated industrial processes. the targeted technologies are thoroughly analyzed, and the resulting implementations combine technological particularities, with the aim of improving communication capabilities on numerous types of devices and operating systems. Given the multitude of communication protocols targeted, the developed gateway applications align with industrial criteria and highlight new perspectives, both from an architectural and applicational point of view. The achieved improvements are presented in the form of precise results, and the advantages and disadvantages of the strategies and methods used are objectively described in relation to the requirements and use cases from the automotive and IoT sectors.

The main objectives are:

1. Development of a Gateway application between OPC UA and SOME/IP protocols, in the context of a Car-to-Infrastructure communication scenario, using the Server-Client and Publish-Subscribe paradigms, to achieve real-time functionality as much as possible;
2. The analysis and improvement of the OPC UA Publish-Subscribe mechanism, in line with automotive industrial requirements, by adapting the architecture for real-time operating constraints and for synchronization of procedures on separate devices;
3. The applicability extension for the OPC UA protocol in the context of image transmission using the Publish-Subscribe mechanism;
4. The development of a gateway application between DDS and OPC UA protocols, analyzing compatibility and efficiency within an architecture that allows the use of the two technologies in both parallel and joint contexts;
5. The development of a configurable multi-protocol gateway solution, which can interface completely separate SOME/IP, DDS, eCAL entities, extending the applicability to V2X concepts and interactions between communication structures specific to different industrial domains.

Given the scope and difficulty of the main objectives, some additional or derived objectives were set within each research phase. This complementary set of objectives clarifies methods and strategies used along the way, and details approaches and results obtained from the numerous experiments and analyses.

A. Analysis of the impact of TSN technology in relation to Ethernet communication protocols;
B. To provide feasible architectural concepts and a synchronization algorithm to improve the Publish-Subscribe UA OPC mechanism;

C. The definition of a multi-channel UDP communication strategy for the use of OPC UA Publish-Subscribe mechanism in the context of image transmission;
D. To define specific criteria and methods to examine high-level communication protocols in diverse systems;
E. To define efficient architectures in cases of interaction between multiple automotive - IoT technologies;
F. To generate quantifiable results that highlight the stability and the real-time operability of the solutions developed during the research phases.

1.3. Publications List

Statistically, a total of 6 scientific papers were produced during the doctoral research, all indexed Web of Science, with the initial paper being presented at a renowned conference. The five subsequent papers were published in prestigious journals, obtaining a cumulative impact factor of 19.235. Further details can be observed based on the listing of the papers, in chronological order by publication date, as follows:

- Chapter 2 is based on the results presented in the following papers:

Ioana and A. Korodi, "VSOMEIP - OPC UA Gateway Solution for the Automotive Industry," *2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 2019, pp. 1-6, doi: 10.1109/ICE.2019.8792619.

Ioana, A.; Korodi, A. OPC UA Publish-Subscribe and VSOME/IP Notify-Subscribe Based Gateway Application in the Context of Car to Infrastructure Communication. *Sensors* 2020, *20*, 4624. https://doi.org/10.3390/s20164624.

- Chapter 3 is based on the results presented in the following paper:

Ioana, A.; Korodi, A. Improving OPC UA Publish-Subscribe Mechanism over UDP with Synchronization Algorithm and Multithreading Broker Application. *Sensors* 2020, *20*, 5591. https://doi.org/10.3390/s20195591.

- Chapter 4 is based on the results presented in the following paper:

Ioana, A.; Burlacu, C.; Korodi, A. Approaching OPC UA Publish–Subscribe in the Context of UDP-Based Multi-Channel Communication and Image Transmission. *Sensors* 2021, *21*, 1296. https://doi.org/10.3390/s21041296.

- Chapter 5 is based on the results presented in the following paper:

Ioana, A.; Korodi, A. DDS and OPC UA Protocol Coexistence Solution in Real-Time and Industry 4.0 Context Using Non-Ideal Infrastructure. *Sensors* 2021, *21*, 7760. https://doi.org/10.3390/s21227760.

- Chapter 6 is based on the results presented in the following paper:

Ioana, A.; Korodi, A.; Silea, I. Automotive IoT Ethernet-Based Communication Technologies Applied in a V2X Context via a Multi-Protocol Gateway. *Sensors* 2022, *22*, 6382. https://doi.org/10.3390/s22176382.

2. OPC UA AND SOME/IP GATEWAY IN THE CONTEXT OF CAR-TO-INFRASTRUCTURE COMMUNICATION

The current research phase defines a series of concrete objectives based on the OPC UA - VSOME/IP interaction:

- The development of a VSOME/IP—OPC UA Gateway in the context of a detailed analysis and development of the OPC UA Publish-Subscribe mechanism with respect to the TSN technology and considering the OSI model;
- Presenting the necessary steps to implement the OPC UA Publish-Subscribe mechanism and to be tested together with the VSOME/IP Notify-Subscribe mechanism using a VSOME/IP—OPC
- Providing a clear view over some intensively stated new concepts that will be of high importance in the vehicle to infrastructure context.

2.1. OPC UA Publish-Subscribe Mechanism

In order for OPC UA to evolve and improve automation in the context of Industry 4.0, for achieving real-time functionality and integration of standard vendor independent hardware with fast communication demands, and also integration in cloud-based infrastructures, the OPC Foundation designed the Publish-Subscribe standard as part 14th of the OPC UA Specifications. When discussing field level communication and controller to controller communication, the needs are represented by low latency in one-to-one transmission. When discussing cloud-based transmission, the context changes in one-to-many or many-to-many transmissions which increase the capabilities of the network. When combining all patterns and different types of devices at large scale, the Publish Subscribe mechanism proves to be suitable in terms of flexibility, performance, and based on the chosen type of transport, permissive on integrating devices with different capabilities in the same context. Based on the OPC Unified Architecture Part 14: PubSub, Publish and Subscribe can use at transport level, different types of protocols based on the information type and network capability. For frequent transmissions and low information volume, UDP transport with binary encoded messages represents a good solution in one-to-one and one-to-many transmissions. For cloud integration and analytics-based applications, standard messaging protocols like MQTT and AMQP are preferred, providing integration of different devices as subscribers on the Middleware level of the Publish Subscribe pattern. Based on the flexibility and easy device integration, real-time requirements must be resolved, and TSN technology creates the possibility of achieving the quality of service regarding synchronization, speed and predictability, and bandwidth-protection, by implementing different Ethernet-specific standards targeting the Data Link Layer, expanding capabilities of the OPC UA in scale and capacity. In the context of relating the concepts, the specifications and the protocols approached by the current study, Figure 1 depicts the relation with respect to the OSI layers of the OPC UA and VSOME/IP application protocols, with the transport layer (e.g., UDP), the network layer, the data link layer, and the physical layer.

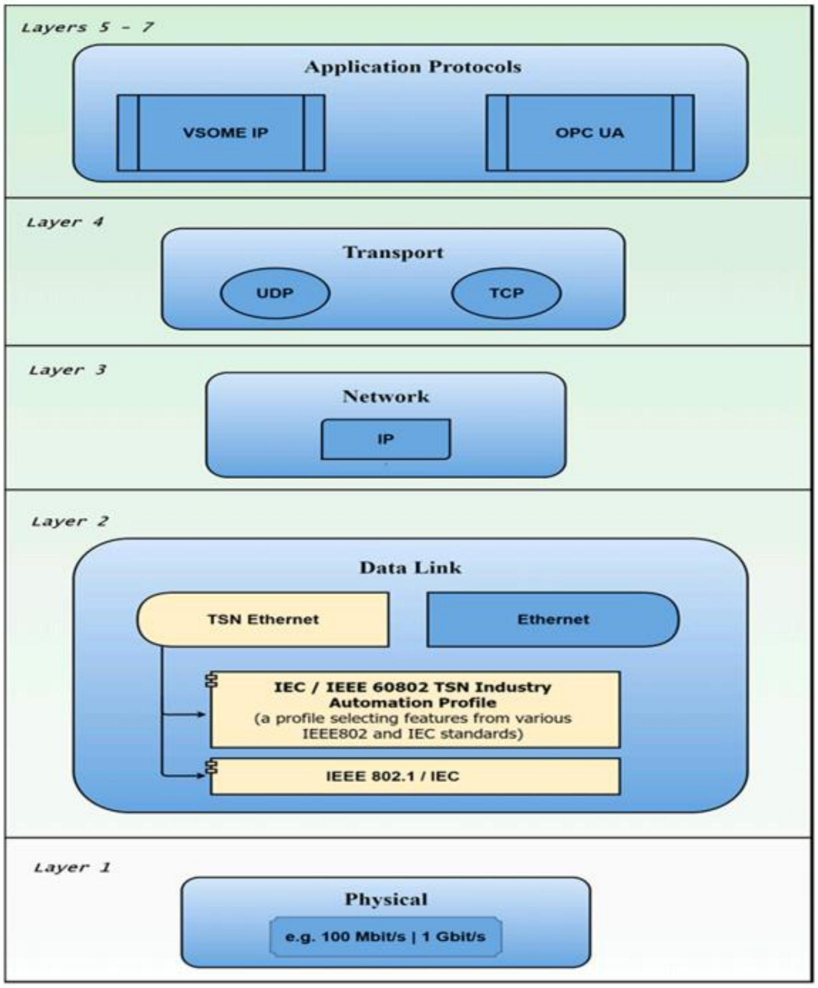


Figure 1. OPC UA and VSOME/IP application protocols in relation UDP, TSN, Raw Ethernet, in the context of the OSI layers.

2.2. System Architecture

Considering the innovative concept of interoperability between two complex high-level protocols and the objective of developing a high-performance Gateway application, and considering that there are no other implementations that place OPC UA and VSOME/IP technologies in the same context, the current research has been structured from a practical point of view in the form of 4 case studies. Each case study contains particularities in terms of the used paradigms , the targeted scenarios and the hardware and software components required. Taking into account these significant differences, a general architecture of the interface concept based on the Gateway application has been defined and can be seen in Figure 2.

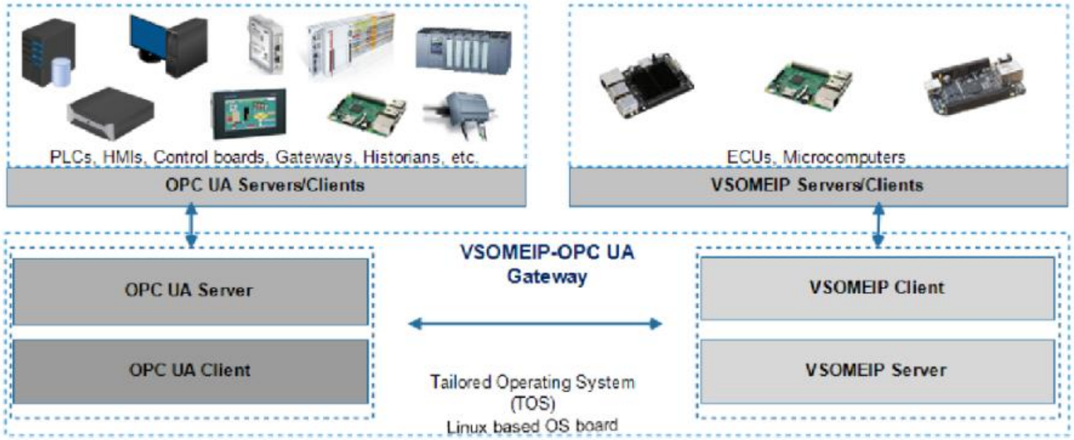


Figure 2: General architecture of the VSOME/IP-OPC UA Gateway concept

Although the differences between the case studies imply changes in relation to the entities developed, a basic architectural structure of the system can be defined, valid in all these cases with minor adjustments depending on the scenario. This architecture is based on 5 entities with different roles as follows:

1. An OPC UA Server/Publisher which stores the data required to be transmitted and is the starting point for data exchange.
2. An OPC UA Client (if entity 1 is of type Server), which modifies the stored data with a configurable recurrence.
3. The Gateway Application - having an OPC UA Client/Subscriber subcomponent responsible for receiving data from the OPC UA provider.
4. The Gateway Application - having a subcomponent in the form of a VSOME/IP service acting as a Server/Notifier, responsible for sending data onwards to the final receiver.
5. A VSOME/IP Client/Subscriber acting as the final data receiver.

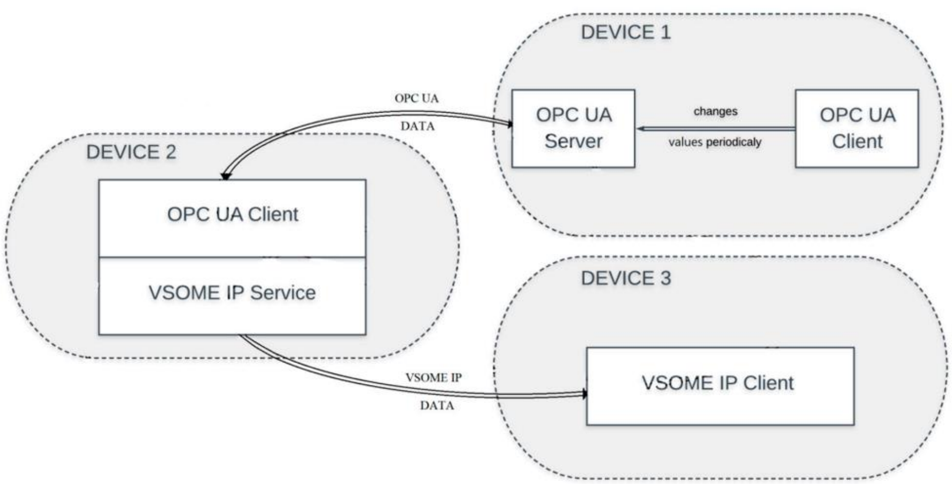


Figure 3 Hardware architecture in relation to the developed entities

2.3. Case study 1

The first case study represents the confirmation of the compatibility of the two protocols used, also highlighting the capabilities of interacting with already validated industrial structures. Following the architectural design and adopting the classical paradigms of Server/Client and Request-Response, the OPC UA entity is considered the provider of the data of interest, being associated to an industrial process (e.g. a smart traffic light). The Gateway application facilitates the reception of the data by the OPC UA Client subcomponent and forwards it to the VSOME/IP Server subcomponent for preparation of delivery to the final VSOME/IP Client receiver. This transmission is structured in 5 steps as follows:

Step 1. The OPC UA server transmits the data (message "0xaa") to the Gateway application.
Step 2. The Gateway application forwards the message to the end receiver.
Step 3. The VSOME/IP client receives the data of interest and prepares an acknowledgement message.
Step 4. The VSOME/IP client sends the acknowledgement message ("0xcc" message) to the Gateway application.
Step 5. The Gateway application receives the acknowledgement message and sends it to the UA OPC Server

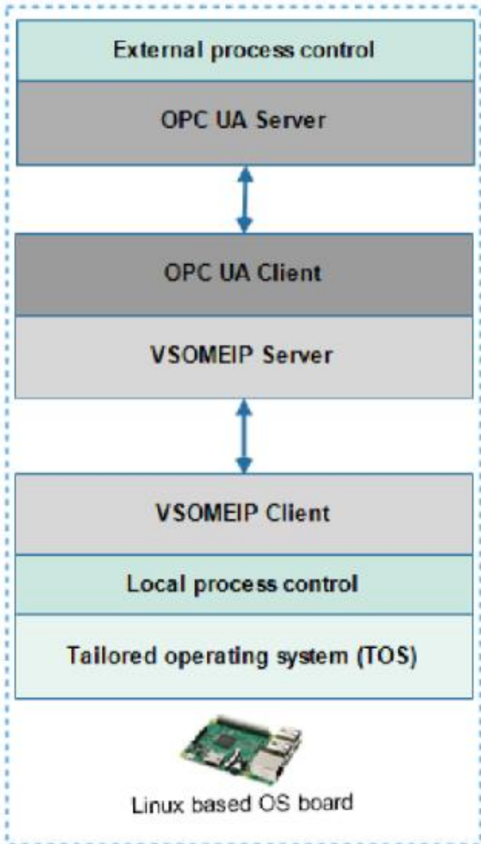


Figure 4. Transmission sequence when placing all entities on the same device

The second phase of the first case study is the interaction between the Gateway application and external OPC UA structures validated in industrial scenarios. Therefore, the targeted scenario implied the connection to an OPC UA Server from a functional plant, associated to a WinCC Professional v13 SCADA Server.

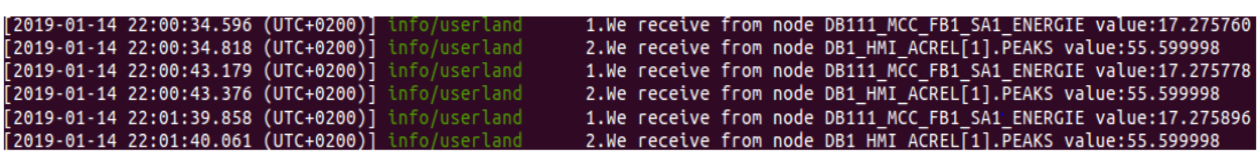


Figure 5. The Gateway application receives valid values from an external OPC UA Server

2.4. Case study 2

Case study 2 focuses on correlating the sent data with the colors and coordinates of a smart traffic light, structuring more concretely the distributed messages and automating the communication process by keeping the OPC UA Client-Server paradigm and adopting the Notify-Subscribe paradigm specific to VSOME/IP.

The browse request - browse response mechanism (UA_BrowseRequest and UA_BrowseResponse) facilitates the filtering of information from different nodes according to node type and data structure. This ability allows future complex OPC UA server architectures to store large volumes of data without the danger of information mixing, providing a high degree of flexibility. Despite this, the Publish-Subscribe mechanism represents a superior solution both in terms of data filtering and integration in use cases with restrictive real-time requirements.

2.5. Case study 3

The third case study implemented for the current concept focuses on the interaction scenario between the Gateway application and three different OPC UA servers, with data being accessed in parallel. This scenario aims to highlight the potential of the system in terms of flexibility and efficiency, offering the possibility of integration into a much larger architecture. The objectives concerning the full transmission speed and accuracy of the delivered data remain valid, using the same test methods and time intervals as in the previous case study. The testing was successfully performed both within a single network and also by placing the devices in different networks. The obtained performances are identical to the previous ones confirming the robust implementation of all entities together with the defined architecture.

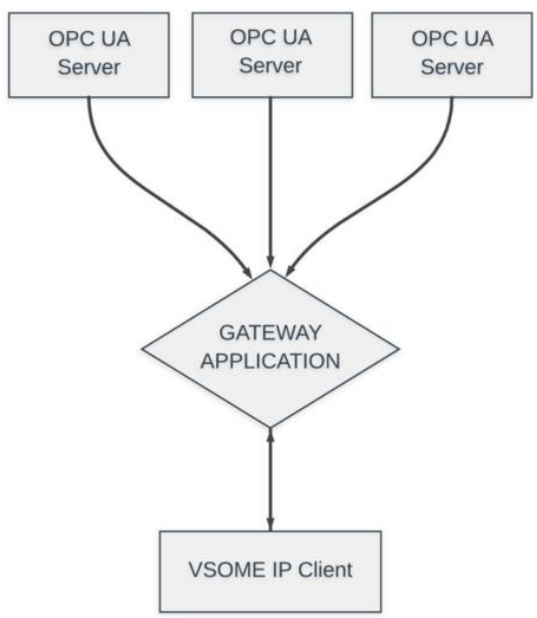


Figure 6. the Gateway Application accessing three different OPC UA Servers

2.6. Case study 4

The implementation of case study 4 is based on the adoption of the OPC UA Publish-Subscribe paradigm together with the similar VSOME/IP Notify-Subscribe paradigm, where the intelligent infrastructure (in this case the traffic light) is represented by an OPC UA Publisher element. The Publisher communicates with the Gateway application through a complementary OPC UA Subscriber subcomponent, following the structure of the application based on two subcomponents. With the shift to paradigms oriented towards automatically distributing data at configurable time intervals, the system evolves significantly towards meeting the needs of real-time, application-level operation. The integration of the two paradigms is done more easily than in case studies 2 and 3, there is no need for an additional entity to update at the right time the values stored by the provider.

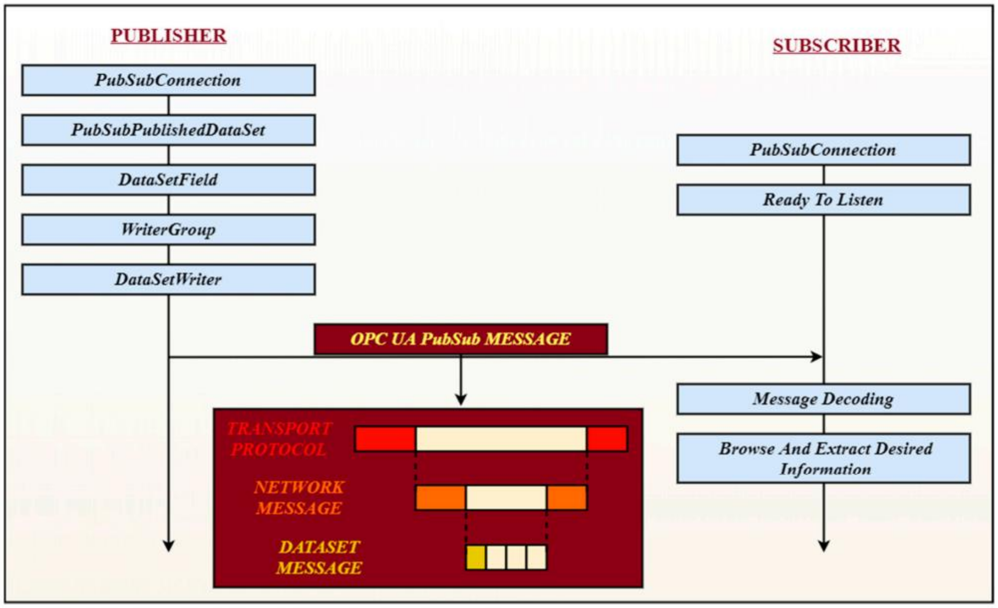


Figure 7. Configuration sequence of the OPC UA Publish-Subscribe mechanism

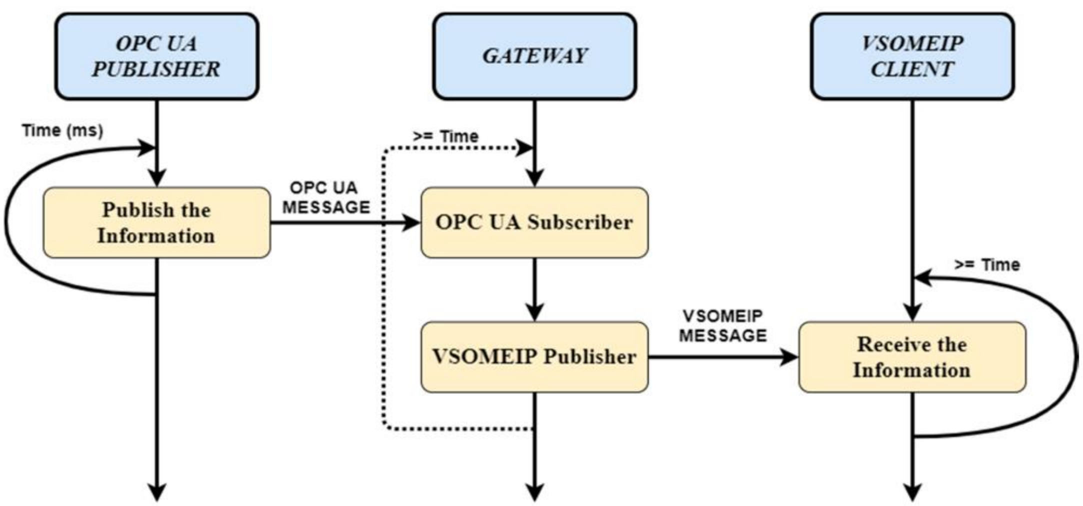


Figure 8. Dependency between Gateway application subcomponents, OPC UA and VSOME/IP in the real-time Publish-Subscribe context

3. IMPROVING OPC UA PUBLISH-SUBSCRIBE MECHANISM IN THE CONTEXT OF REAL-TIME COMMUNICATION

The objectives of the current research phase are the following:

- To provide an analysis of the OPC UA interfacing using the Publish-Subscribe paradigm regarding real-time constraints and role distribution between entities, considering the current status of developments and some well-founded interfacing strategies from the automotive sector;
- To conceive and implement a solution regarding OPC UA Publish-Subscribe over UDP mechanism focused on a synchronization algorithm and a multithreading broker application that achieves real-time reactions and higher efficiency in order to extend the QoS and the applicability of the interfacing. The solution foresees to reduce the magnitude of the loosely coupled subscriber and publisher, the difficulty of sending larger volumes of data for various subscribers at high speeds, and the charge on the network and services in terms of polling and filtering. Availability and safety have to guide the approach, in that the solution must handle faults occurrence, focusing on fault detection, tolerance, and recovery

3.1. Publish-Subscribe Mechanism: Design and Architecture

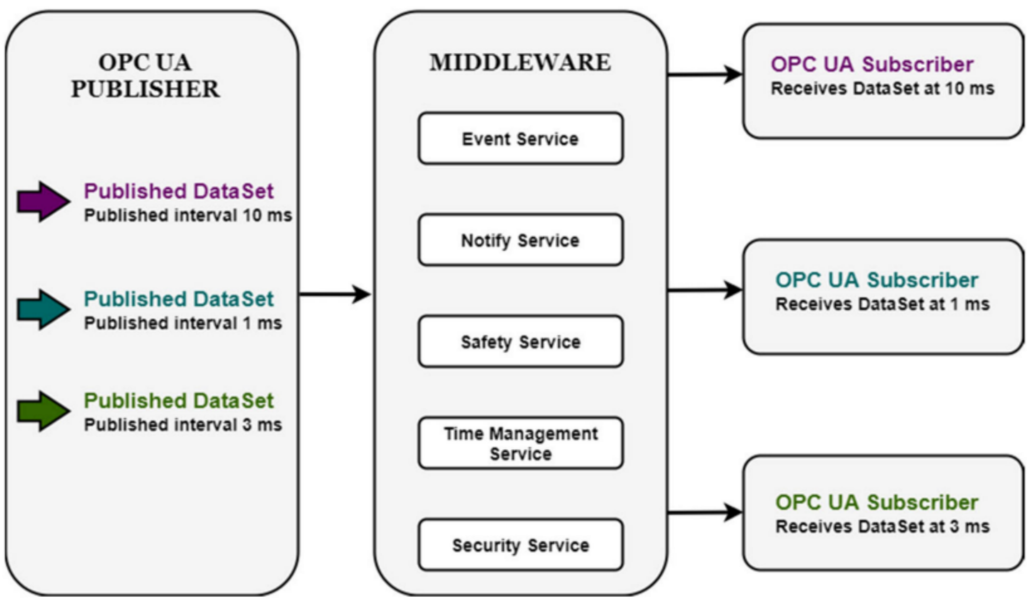


Figure 9. Hypothetical/Proposed Middleware Design with Services, in real time scenarios

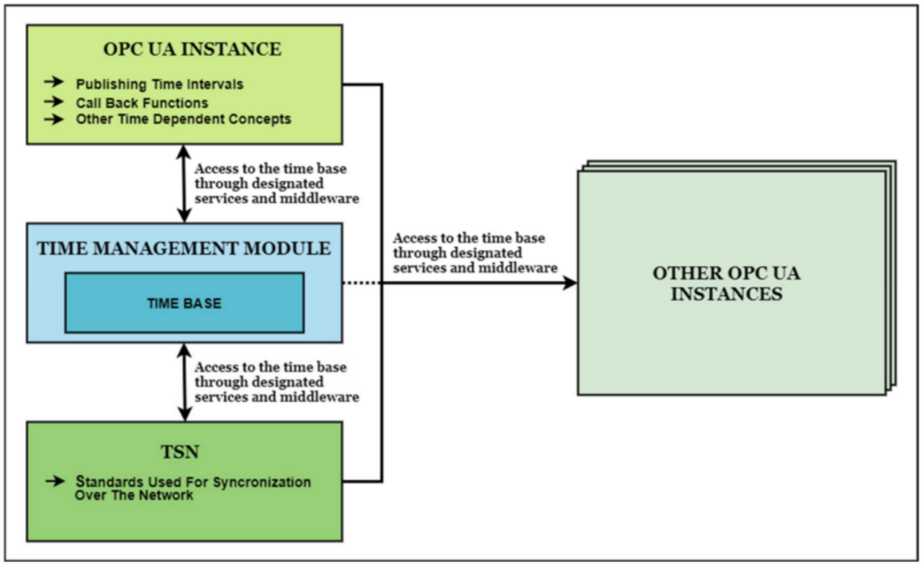


Figure 10. Proposed design with all entities relying to a common time base

3.2. System architecture

The purpose of the broker application is to interface the Publisher and the Subscribers in an efficient manner, keeping the implementation close the specifications. Having more entities present, the approach is to have each entity running on a separate device, with Linux-based OS as seen in Figure 11.

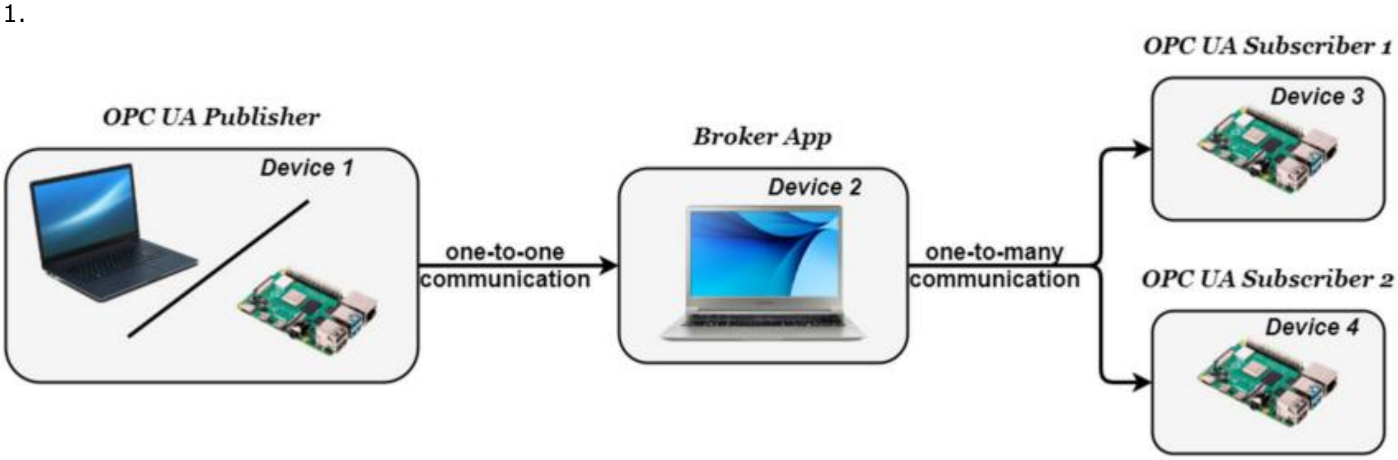


Figure 11. System Architecture

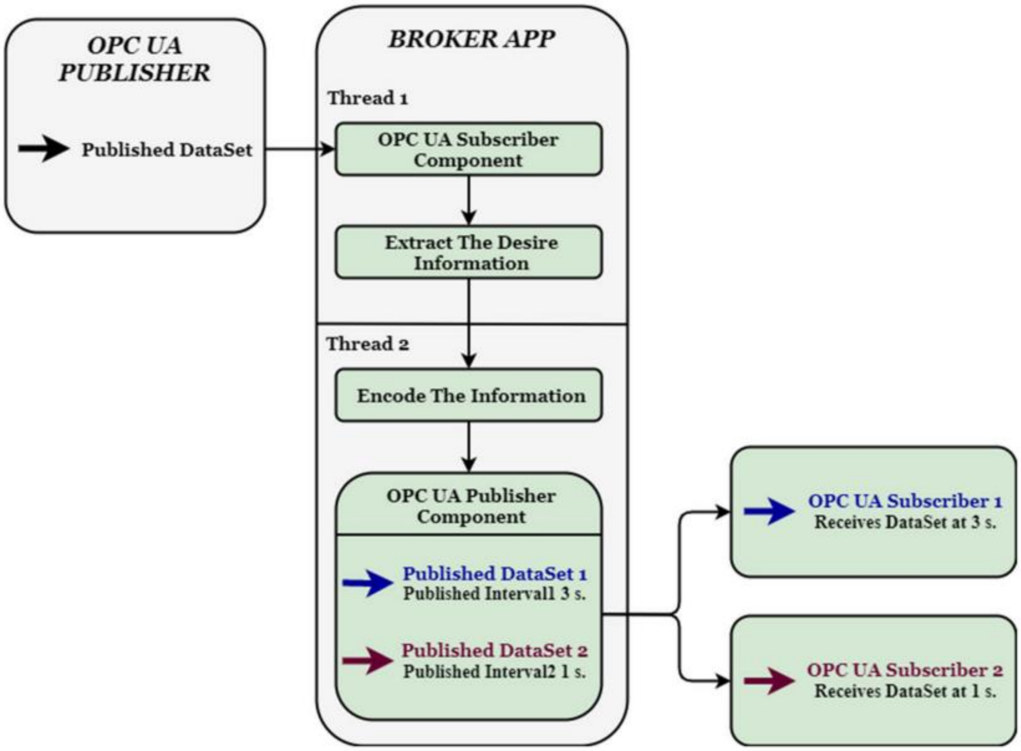


Figure 12. Architecture and Interaction of the Broker Application

With the broker application in place and with the subscribers expecting the correct messages at the correct time, for the best-case scenario, all configurations are correct. However, there are scenarios where only the right configuration of timing details for both the broker and the Subscribers is not enough for achieving real time synchronization between entities that do not have a common time base and do not exchange constantly time references through a notification mechanism. In these cases, the challenge is to synchronize separate entities in a dynamic way knowing the approximative intervals of transmission and receive operations.

The implemented synchronization algorithm proves efficient and the testing of the implementation has confirmed that desired behavior is present on the broker application and on the Subscribers.

3.3. Results

Following the implementation phase, a number of concrete results and claims can be observed. The implementation of the Broker application together with Publisher and Subscriber entities has been successful, proving that this concept can be functional. Major architectural goals have been achieved, providing concrete advantages for OPC UA communication.

Table 1: Case study results analysis

Entity	Advantages	Disadvantages	Achievements
OPC UA Publishers	• moderate difficulty in implementation • easy configuration for different		• easy way of sending larger amounts of data for multiple subscribers with

	subscribers with different expectation • totally decoupled from the consumers of the information		different expectation
Broker App	• multithreading capabilities • real time capabilities	• high complexity in implementation • an initial first step is needed for obtaining subscribers preferences and IDs (hard-coded information in the current implementation)	• real time behavior and synchronization with the subscribers • data buffering • backup publisher • safety capabilities in case the publisher is shutting down
OPC UA Subscribers	• easy/moderate difficulty in implementation • totally decoupled from the provider of the information • synchronization capabilities based on the described Synchronization Algorithm	• an initial first step is needed for transmitting preferences and ID (hard-coded information in the current implementation)	• real time behavior and synchronization with the Broker App • less polling of the network • less filtering for the desired information

4. APPROACHING OPC UA PUBLISH-SUBSCRIBE IN THE CONTEXT OF IMAGE TRANSMISSION

The Open Platform Communication Unified Architecture (OPC UA) protocol is a key enabler of Industry 4.0 and Industrial Internet of Things (IIoT). OPC UA is already accepted by the industry and its presence is expected to reach more and more fields, applications, and hierarchical levels. Advances within the latest specifications are providing the opportunity to extend the capabilities and the applicability of the protocol, targeting better performances in terms of data volumes, speed, availability, footprint, and security. Consequently, the research proposes to extend the applicability of the OPC UA in the context of image transmission. Although highly needed, the image transmission after processing is currently beyond the reach of OPC UA or other legacy industrial protocols, being considered as a separate fraction in the industrial environment. The concept and developments are applied considering both the end-of-line industrial manufacturing process in the automotive sector and the car-to-infrastructure communication. Without special hardware constraints, the obtained results are proven to be appreciable, opening various future perspectives for image transmission using OPC UA.

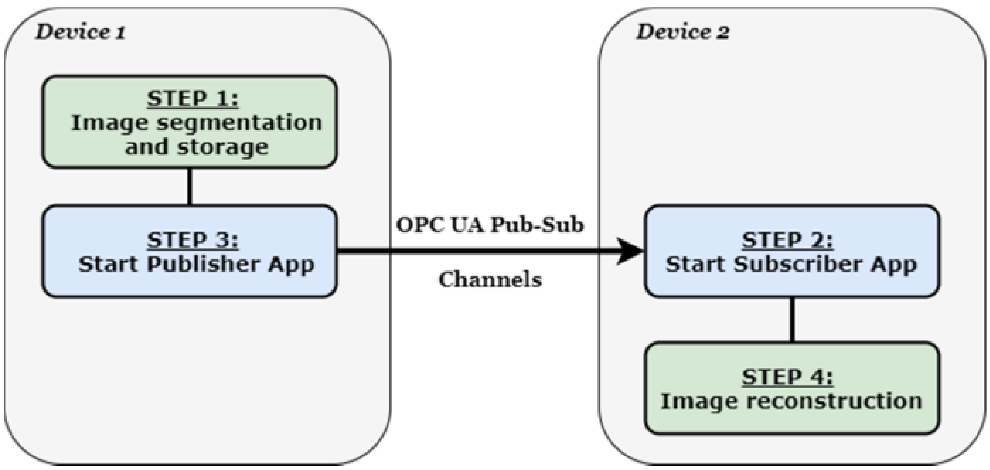


Figure 13. Open Platform Communication Unified Architecture (OPC UA) publish–subscribe image transmission steps

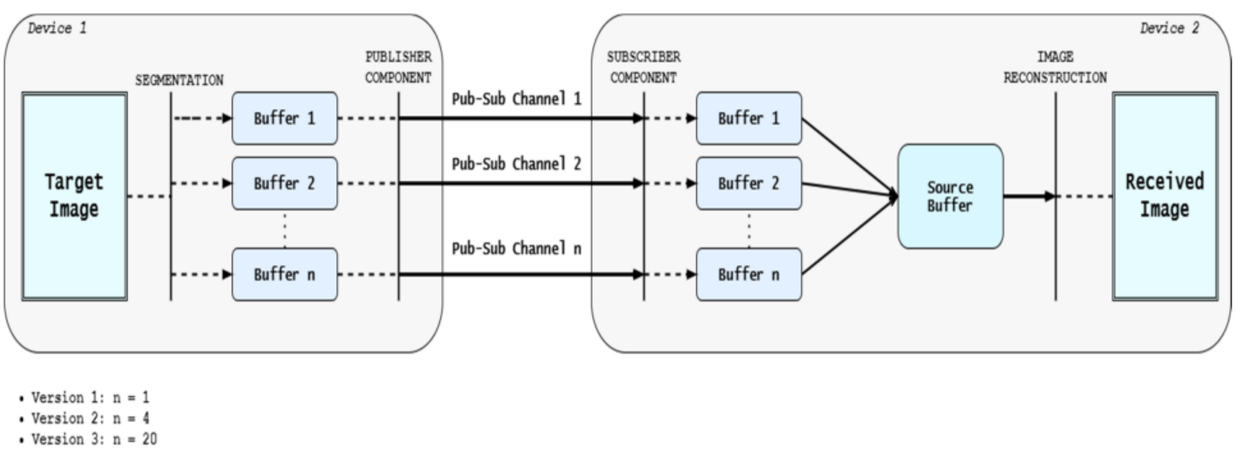
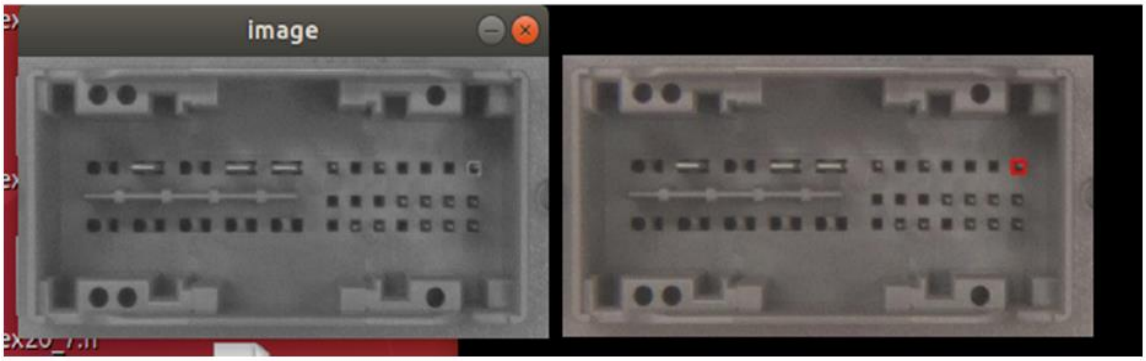


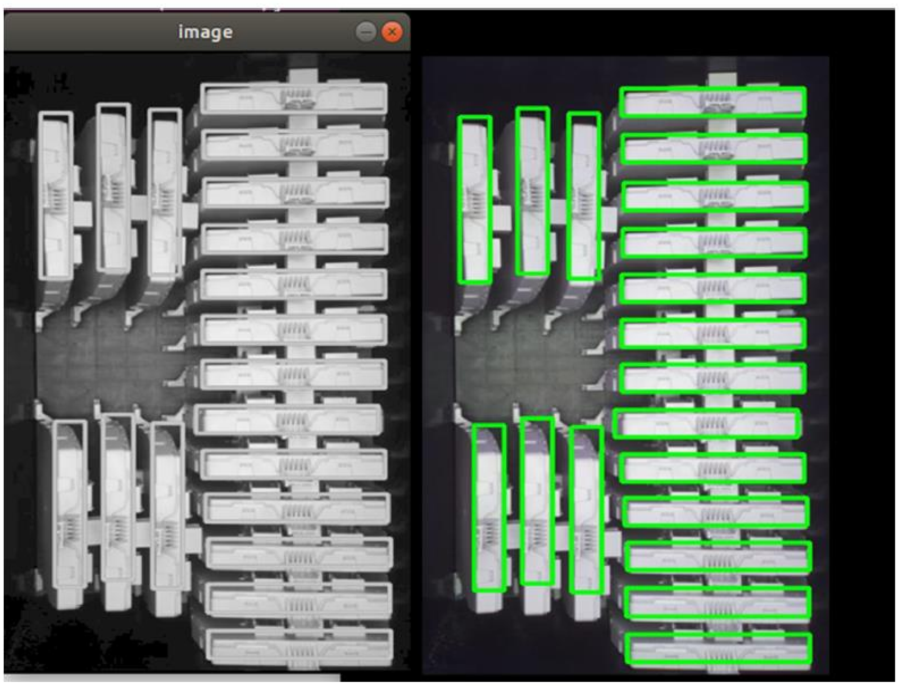
Figure 14. General system architecture

The OPC UA pub/sub mechanism can produce complex applications with real-time requirements and can expand the current use of the protocol towards other functionalities or other domains. The author is not aware of other work toward image transmission through OPC UA. Based on the popularity of the protocol in the industry and with the evolution of the integrated technologies and mechanisms, these implementations with certain achieved goals can resolve or improve current scenarios and provide a step forward toward interconnectivity in the IIoT context.



(a) (b)

Figure 15. OPC UA publish–subscribe, 20-channel image transmission for ECU automatic optical inspection process in the automotive manufacturing: (a) the received image and (b) the target image



(a) (b)

Figure 16. OPC UA publish–subscribe, 20-channel image transmission for packaging boxes in the automotive manufacturing: (a) the received image and (b) the target image

With the successful transmission of images over the OPC UA publish–subscribe mechanism, the applicability of the OPC UA protocol extends to new functionalities and confirms the high applicability of the publish–subscribe paradigm in future developments with the possibility of achieving industrial demands. The current performances and the real-time behavior can be improved in the context of TSN technology. This concept provides ways of implementing applications with high capabilities in exchanging information at high rates between different devices over Ethernet, assuring the necessary objectives toward IIoT and Industry 4.0.

5. DDS AND OPC UA PROTOCOL COEXISTENCE SOLUTION IN REAL-TIME AND INDUSTRY 4.0 CONTEXT

Continuing the evolution towards Industry 4.0, the industrial communication protocols represent a significant topic of interest, as real-time data exchange between multiple devices constitute the pillar of Industrial Internet of Things (IIoT) scenarios. Although the legacy protocols are still persistent in the industry, the transition was initiated by the key Industry 4.0 facilitating protocol, the Open Platform Communication Unified Architecture (OPC UA). OPC UA has to reach the envisioned applicability, and it therefore has to consider coexistence with other emerging real-time oriented protocols in the production lines. The Data Distribution Service (DDS) will certainly be present in future architectures in some areas as robots, co-bots, and compact units. The current paper proposes a solution to evaluate the real-time coexistence of OPC UA and DDS protocols, functioning in parallel and in a gateway context. The purpose is to confirm the compatibility and feasibility between the two protocols alongside a general definition of criteria and expectations from an architectural point of view, pointing out advantages and disadvantages in a neutral manner, shaping a comprehensive view of the possibilities. The researched architecture is meant to comply with both performance comparison scenarios and interaction scenarios over a gateway application. Considering the industrial tendencies, the developed solution is applied using non-ideal infrastructures to provide a more feasible and faster applicability in the production lines.

Considering the current situation, this research phase proposes the following objectives:

- Define specific criteria that allow the examination of DDS and OPC UA in an unideal system, taking in consideration multiple challenges from the industry.
- Analyze the real-time behavior for DDS and OPC UA, implementing the necessary mechanisms for the process.
- Define an architecture that is suitable for parallel usage of DDS and OPC UA, that also offers the possibility for the two communication protocols to interact.
- Implement a DDS—OPC UA gateway application

5.1. System Architecture

The defined architecture was meant to comply with both performance comparison scenarios, and also with interaction scenarios over a gateway application, with the purpose of confirming the compatibility and feasibility between DDS and OPC UA alongside a general definition of criteria and expectations from an architectural point of view.

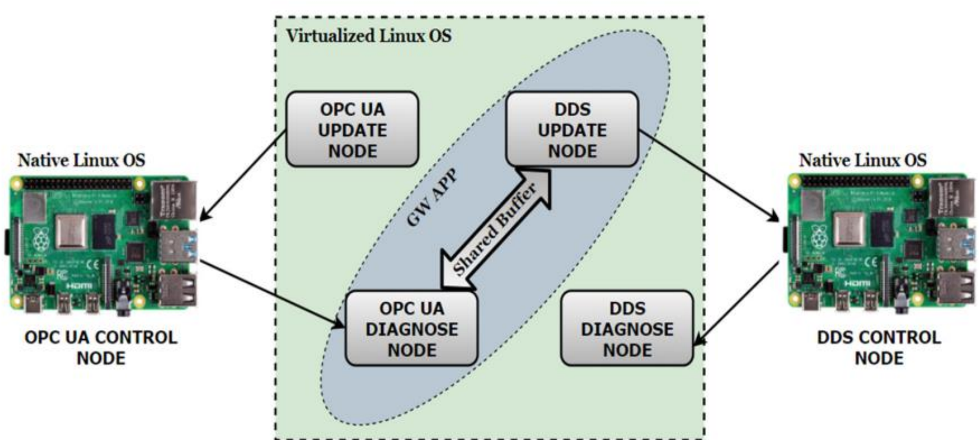


Figure 17. System architecture

The development of applications for multiple device communication set-ups must assure high efficiency and good resource management on all devices. For the current study, the Publish-Subscribe mechanism was used for both communication protocols, targeting real-time behavior at the application level for all nodes.

The current work focuses on two case studies. The first one targets observations on how each communication protocol reacts in accordance with the operating system for operations executed at different time recurrences. It analyzes how efficiently the technologies behave when running on operating systems without enhanced real-time capabilities and using a network that does not offer time guarantees for packet transmission. The second case study proposes a gateway solution for scenarios where protocol interaction is required. The switch between the two use cases can be performed with little effort at configuration and no architectural changes.

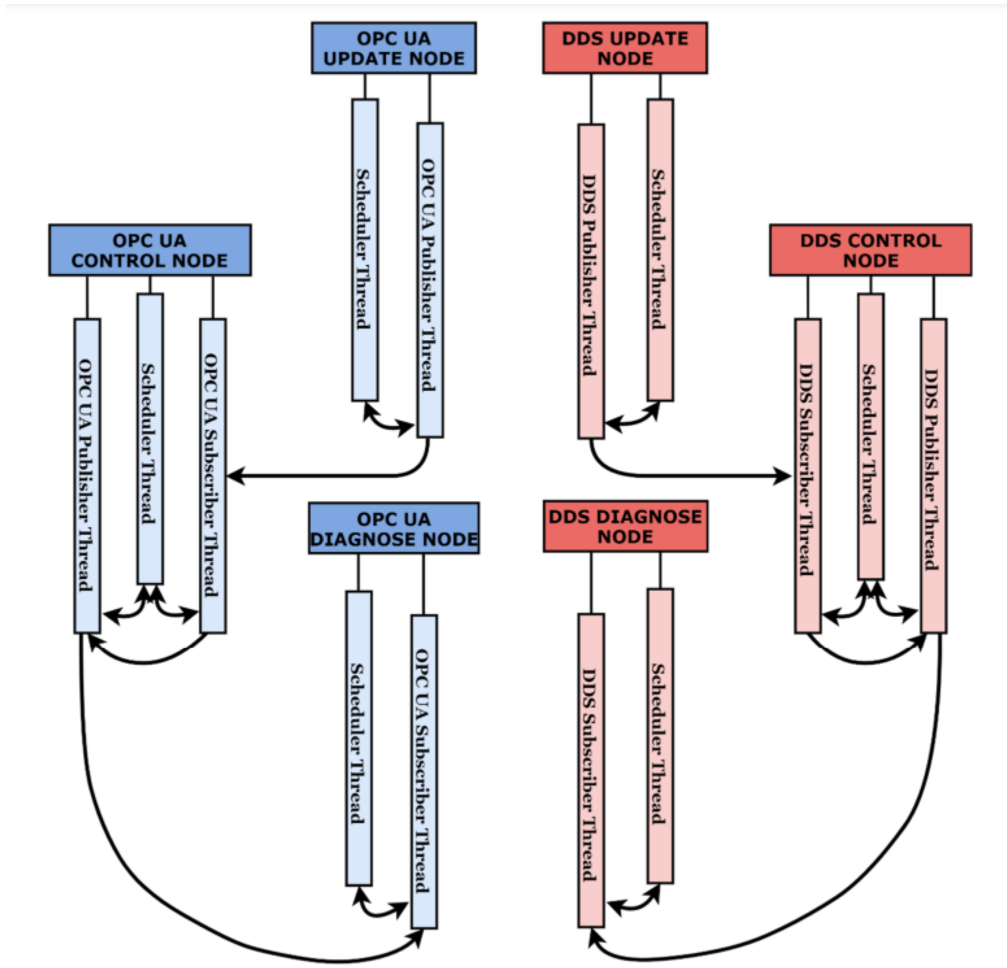


Figure 18. Multithreading nodes from an architectural perspective

5.2. Case study 1 results

The results for the functions call verification process can be observed in Tables 2–5 for DDS, and in Tables 6–9 for OPC UA for the first criteria of the case study. The Tables present success rates for each time recurrence.

Table 2. DDS Update Node—Virtualized Linux OS—Publish Operation.

Publish Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈90%	≈74%	≈64%
TOTAL Number of Tests: 2790			

Table 3. DDS Control Node—Native Linux OS—Publish Operation.

Publish Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈93%	≈84.6%	≈77%
TOTAL Number of Tests: 2865			

Table 4. DDS Control Node—Native Linux OS—Subscribe Operation.

Subscribe Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈85%	≈65%	≈48.5%
TOTAL Number of Tests: 2805			

Table 5. DDS Diagnose Node—Virtualized Linux OS—Subscribe Operation.

Subscribe Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈85%	≈65%	≈47%
TOTAL Number of Tests: 3015			

Table 6. OPC UA Update Node—Virtualized Linux OS—Publish Operation.

Publish Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈95%	≈81.2%	≈56%
TOTAL Number of Tests: 2685			

Table 7. OPC UA Control Node—Native Linux OS—Publish Operation.

Publish Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈100%	≈87%	≈56%
TOTAL Number of Tests: 2970			

Table 8. OPC UA Control Node—Native Linux OS—Subscribe Operation.

Subscribe Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈100%	≈91%	≈85%
TOTAL Number of Tests: 3015			

Table 9. OPC UA Diagnose Node—Virtualized Linux OS—Subscribe Operation.

Subscribe Operation—Recurrent Execution Check			
10 ms	5ms	2ms	1ms
≈100%	≈87.5%	≈77%	≈64%
TOTAL Number of Tests: 3015			

The second criteria of Case Study 1 focus on the data-buffering mechanism designated to highlight how OS and device desynchronization influence the receiving data, offering statistical results at different time intervals. The results can be observed in Figure 19.

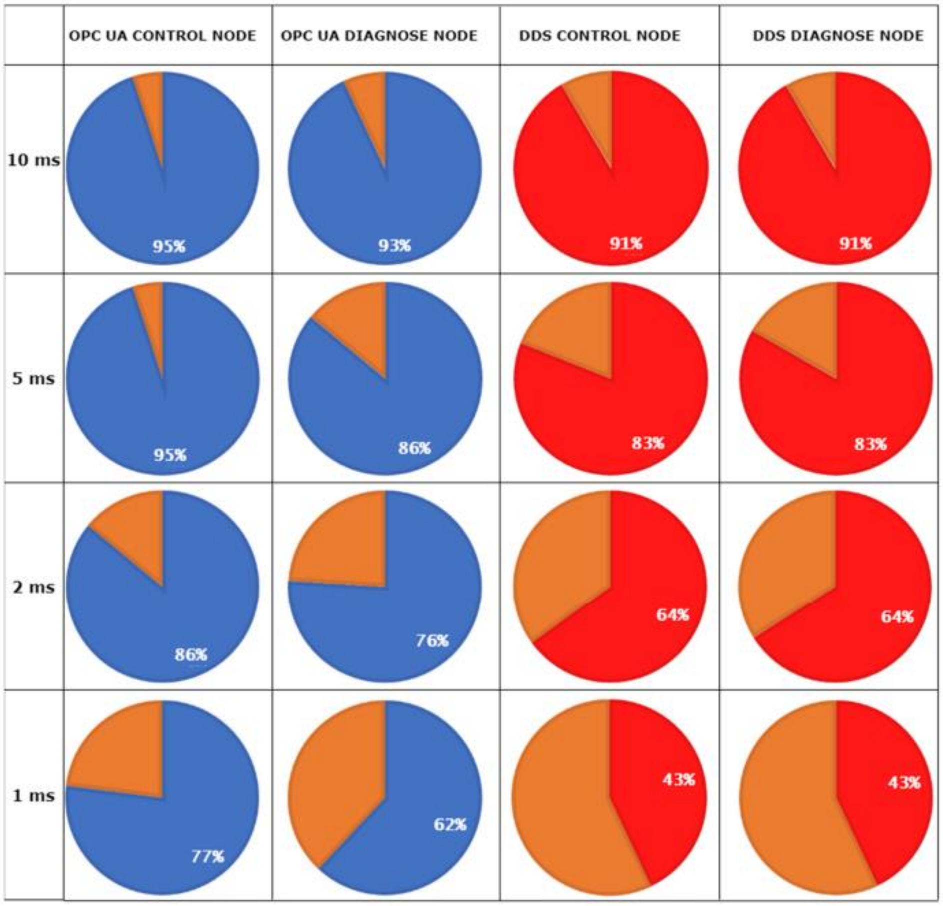


Figure 19. Data-buffering success rate percent-based results.

The result for the data-buffering process on the Subscribers side confirms the results obtained from the recurrent function call verification. The numbers are proportional for both criteria, with expected decreased percentage values for the data-buffering process, validating the additional impact that the network stability has for the data exchange procedure, over the already existent impact generated from OS real-time limitations. Although at under 5 ms intervals, the differences between the protocols seems to slightly increase, there are still uncertainties regarding how much the interaction and data exchange between the protocols can be affected, a gateway scenario being of interest in this case.

5.3. Case study 2 results

For Case Study 2, the main objective was the implementation of a gateway application for the current architecture, offering the possibility to acknowledge the feasibility of DDS and OPC UA in IIoT multi-device scenarios. Having a gateway application for cross-domain control and data exchange operations through Ethernet technologies confirms the high capabilities of two well-established communication protocols and expands the possibilities towards future advancements. The impact of Ethernet protocols in hard real-time use cases is difficult to estimate. Even if there are numerous solutions available and compliant with real-time demands, the general understanding must not focus on how fast a communication protocol is able to deliver data, but rather, how stable the delivery is, at what time intervals the exchange can fail, and what are the factors that can influence the performance of the chosen protocol. The current development suggests a detailed exemplification of how the above-described impact can be observed and understood even in scenarios where the data are delivered at fast recurrences.

There are two types of messages are sent alternately to the gateway application, which serves as an OPC UA subscriber to the control node and as a DDS publisher to the DDS control node. Once the message is received by the DDS control node, a digital signal is generated accordingly to the type of the received message (corresponding to high or low states) simulating the control of an actuator that requires fast recurrent pulses. The generated digital signal is monitored using an oscilloscope. Thus, for each time interval set for data exchange between nodes, the signal is measured, offering the possibility to confirm the length and frequency of the pulses, meaning that the whole propagation of the data through the architecture can be measured. The expected desynchronizations and stability problems that may occur for under 10 ms intervals can be visualized with ease, and the qualitative degradation of the signal can be observed in a significant manner. This provides a suggestive perspective upon the necessity for additional technologies capable of guaranteeing the time synchronization between devices and network stability in IIoT use cases. The gateway application facilitates the propagation of the data between multiple nodes, devices, and distinct protocols and operating systems without different configuration needed for the already implemented software. The solution confirms that both OPC UA and DDS are compatible and feasible for such scenarios, even in unideal systems, increasing the potential towards more complex and scalable applications for multiple industrial domains.

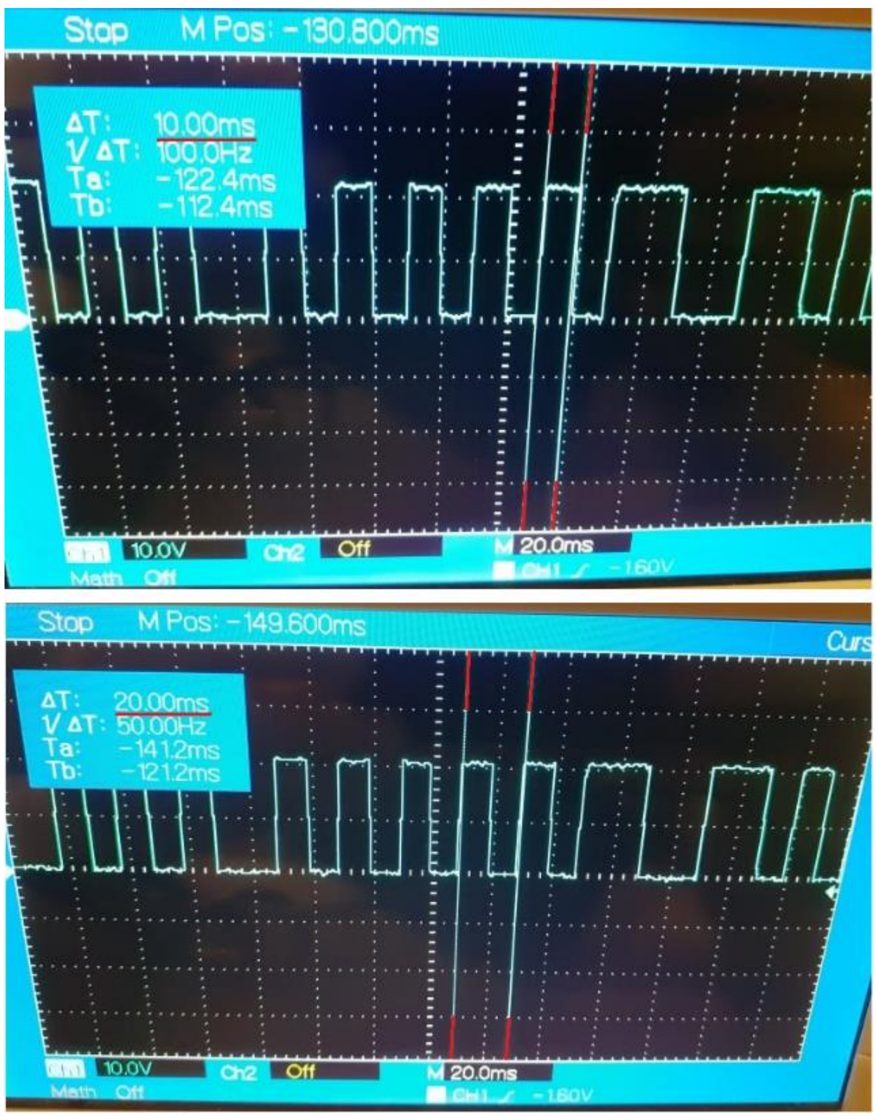


Figure 20. Generated Digital Signal based on payload delivered by the Gateway Application at 10 ms recurrence

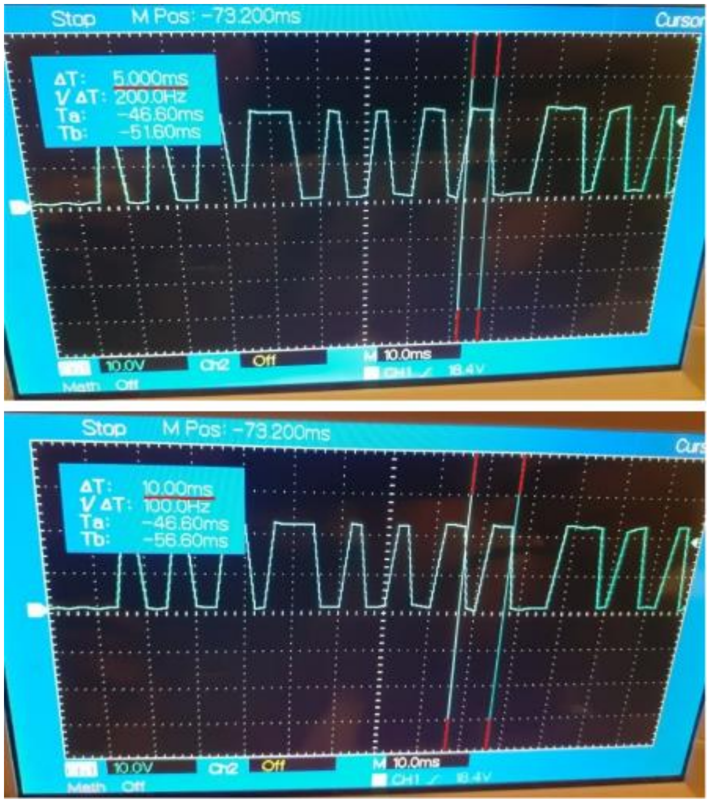


Figure 21. Generated Digital Signal based on payload delivered by the Gateway Application at 5 ms recurrence.

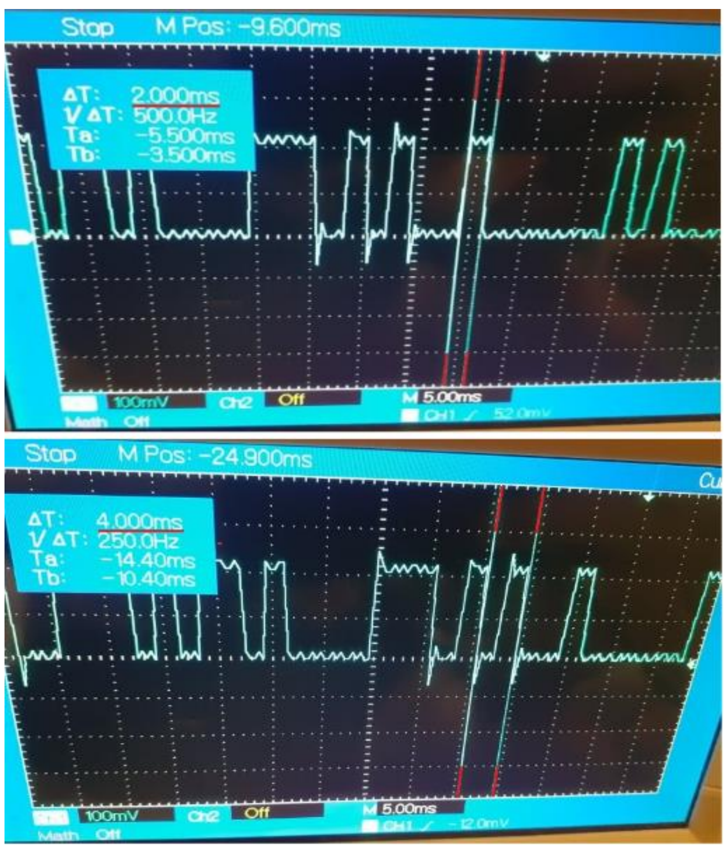


Figure 22. Generated Digital Signal based on payload delivered by the Gateway Application at 2 ms recurrence

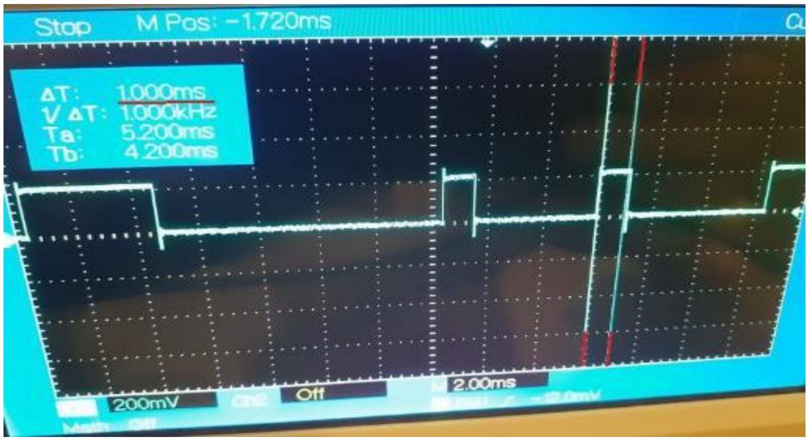


Figure 23. Generated Digital Signal based on payload delivered by the Gateway Application at 1 ms recurrence

With the proposed architecture and concept, respectively with the case studies implemented proficiently, and based on the obtained results, the following objectives of the current work have been achieved:

- The two defined criteria for the examination of DDS and OPC UA behavior provided a complex perspective towards the capabilities of the selected protocols in a system that considers current challenges specific to multi-device communication over the Ethernet. The potential of the current criteria can extend to future developments that address specific improvement steps, or can be adapted to multiple particular systems and technologies with similar goals.
- The implemented mechanisms used to analyze the real-time behavior of DDS and OPC UA confirmed a high level of efficiency, and the obtained quantifiable results expand the current perception regarding the targeted technologies to new industrial and research areas.
- The defined architecture has proved to be reliable for both common and parallel usage of the protocols, delivering the desired level of flexibility and scalability. The diversity of industrial factors that disfavor the ideal responses from DDS and OPC UA adds authenticity to the experiment and allows the adoption of similar architectural concerns to a wide range of applications.
- The development of the OPC UA—DDS gateway application expands the applicability of the protocols to cross domain scenarios, reconfirms the feasibility and high quality of service claims for both technologies and in the current context, it offers a practical viewpoint concerning compliance to real-time requirements.

6. AUTOMOTIVE IOT ETHERNET-BASED COMMUNICATION TECHNOLOGIES APPLIED IN A V2X CONTEXT VIA A MULTI-PROTOCOL GATEWAY

The architectural approach for complex communication systems must adapt quickly and take into consideration the increasing set of requirements for every industrial field. The automotive domain is evolving toward the electrification era, with massive technological transformations being realized on all architectural, hardware, and software levels. The legacy usage of exclusively microcontrollers is altered by adopting microprocessors with extended functionalities, reshaping the development structure. Although new hardware capabilities are available and Ethernet communication protocols can contribute to a new range of use-cases for intra-car or for vehicle-to-X (V2X) communication, the implications of using multiple protocols that cover different types of requirements, in the same architecture, are not fully determined. The importance of establishing clear expectations for intelligent communication systems considering various technological and architectural factors is significant for future improvements. In the current paper, we examine the compatibility and real-time responsiveness capabilities, in a diverse, service-oriented architecture, for the major automotive IoT Ethernet-based communication technologies. The feasibility analysis is materialized in a multi-protocol gateway solution that facilitates data exchange between entities with different technological origins. Scalable Service-Oriented Middleware over IP (SOME/IP) is considered the relevant protocol in the automotive domain, alongside the Data Distribution Service (DDS), which combines automotive and IoT applicability. The enhanced Communication Abstraction Layer (eCAL) middleware is added to the mix as an alternative solution for future communication scenarios. The obtained results confirm the compatibility between the targeted technologies, offering a clear understanding regarding the limits of a complex multi-protocol communication system. The defined service-oriented architecture offers efficient data exchanges in a gateway context, also allowing the exploration of the real-time capabilities.

Considering the aforementioned context, the current study has the following objectives:

- Analyze the compatibility of the selected communication technologies, combining strategies and visions with high potential and highlighting advantages and disadvantages from multiple perspectives, allowing a better understanding of how each protocol can be used in the right context.
- Define an appropriate architecture aligned with the latest adaptive architectural principles that includes necessary elements for increased applicability in automotive and IIoT applications, and addresses challenges specific to Ethernet technologies.
- Conceive and develop a configurable multi-protocol gateway solution that can interface completely separated SOME/IP, DDS, and eCAL entities, expanding the applicability towards V2X concepts and interactions between communication structures specific to different industrial fields.
- Explore real-time capabilities of the multi-protocol gateway solution, examining the possible impact of future achievable improvements and establishing a clear set of expectations concerning the evolving industrial requirements.

6.1. Automotive Applicability Study

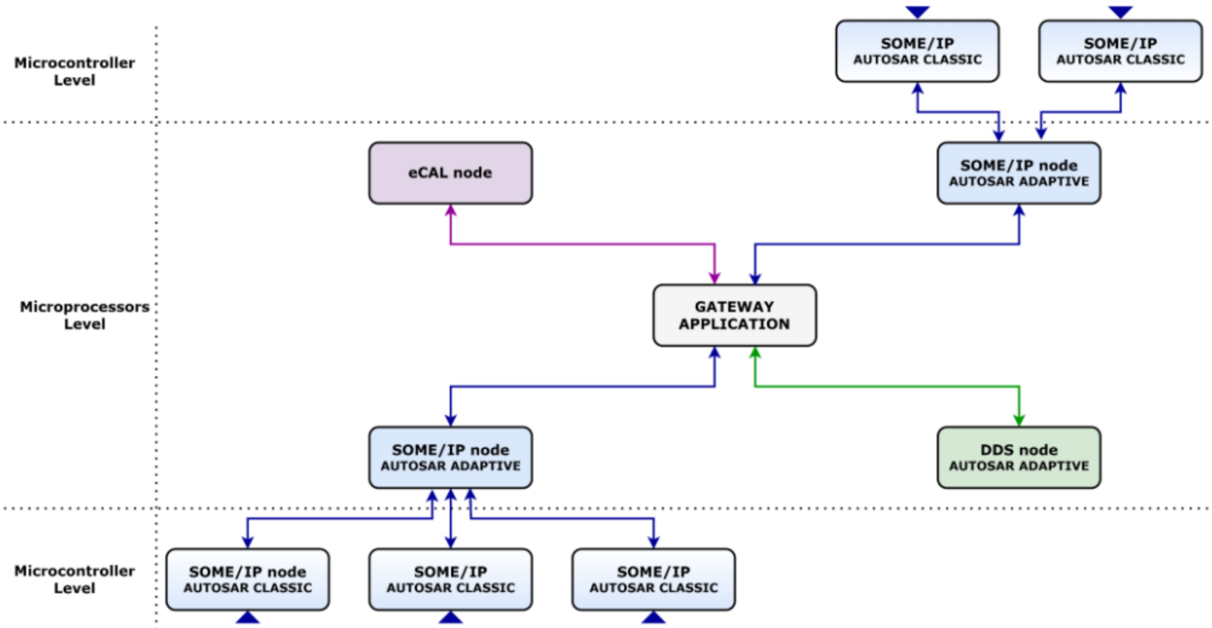


Figure24. First industrial applicability perspective for the multi-protocol gateway

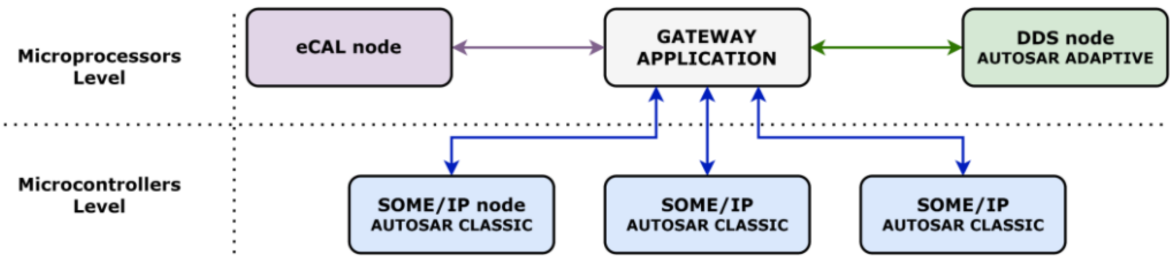


Figure 25. Second industrial applicability perspective for the gateway solution

6.2. System Architecture

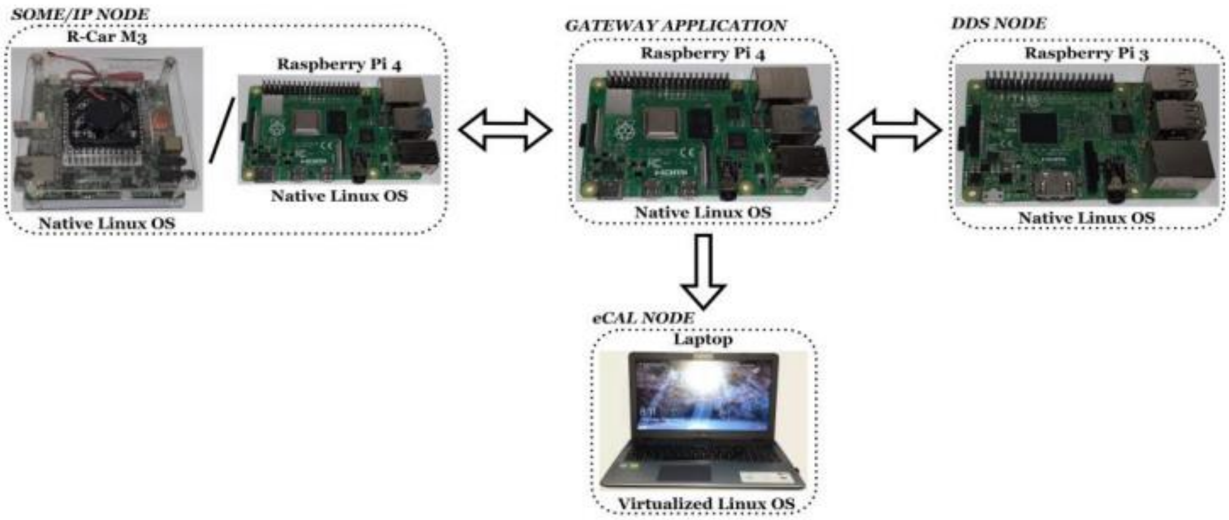


Figure 26. Hardware architecture

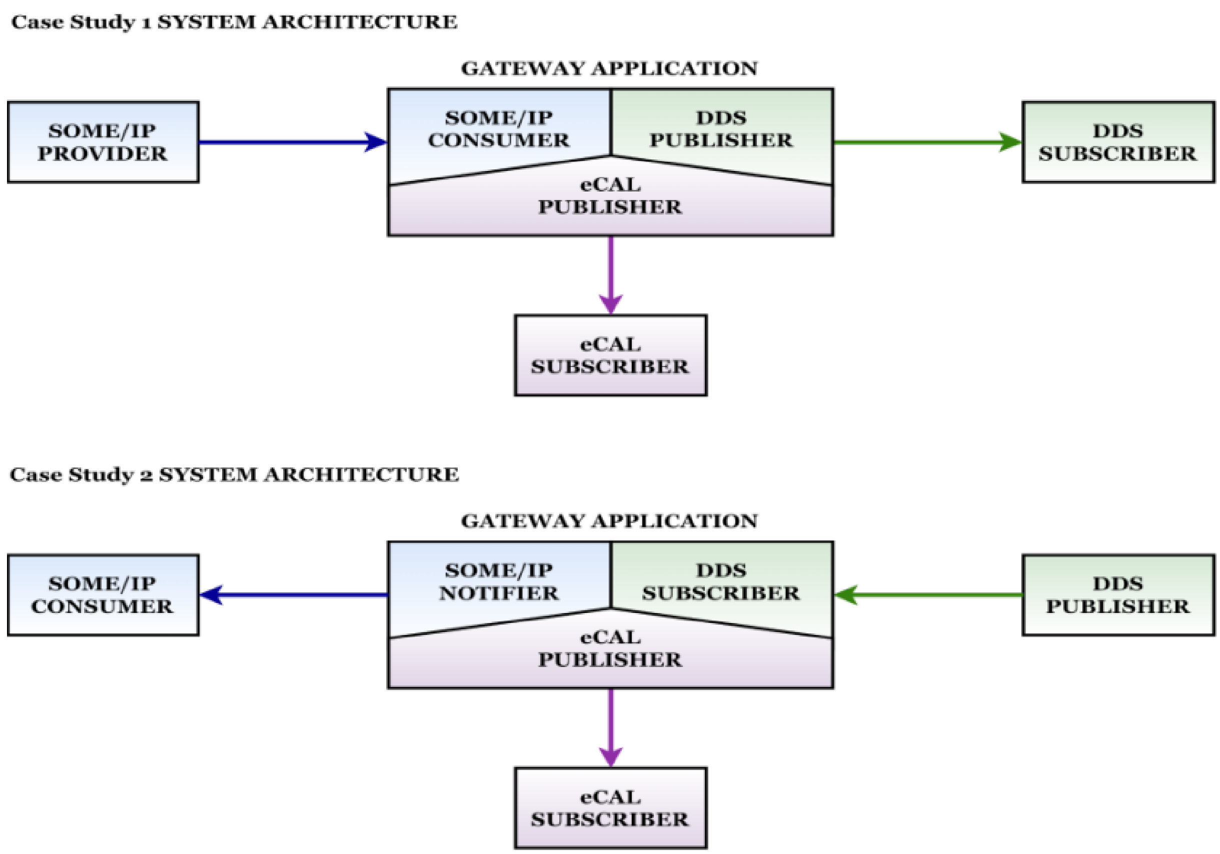


Figure 27. System architecture showcasing both versions of the gateway

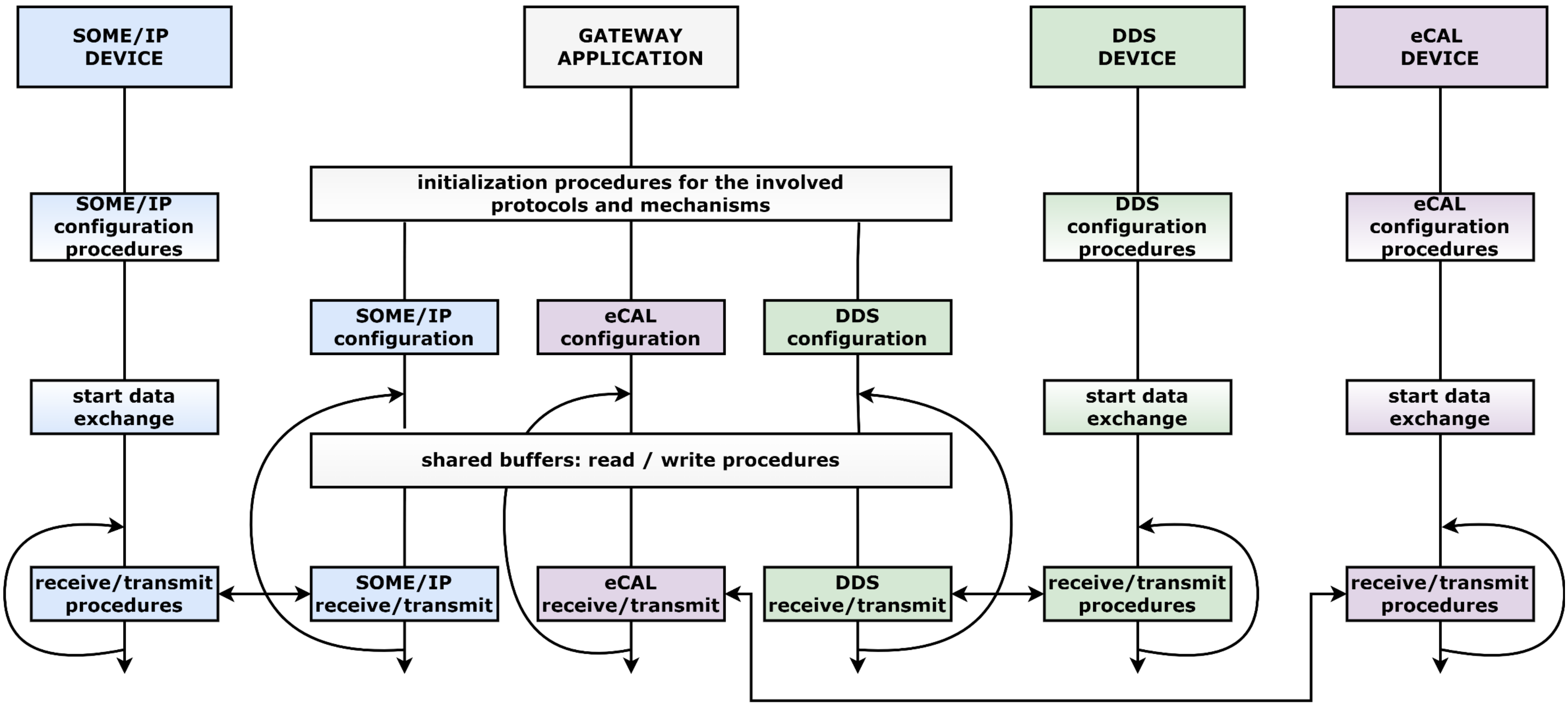


Figure 28. Procedure sequence for all nodes of the architecture

Objectives of case study 1 and 2 targeting the reliability and efficiency of the concept are analyzed by conceiving and developing a data buffering mechanism and a signal generating mechanism for the distributed heartbeat event. Each mechanism provides clear results concerning the behavior of the communication infrastructure when taking into consideration real-time requirements and the impact that the network can have on the delivery of messages at fast recurrences. The data buffering capability is considered an important feature in IoT industrial communication systems. For the current scenarios, the data buffering is important for a better understanding of the obstacles that may emerge in complex SOAs. The conceived and developed data buffering process is detailed from an architectural perspective in Figure 29.

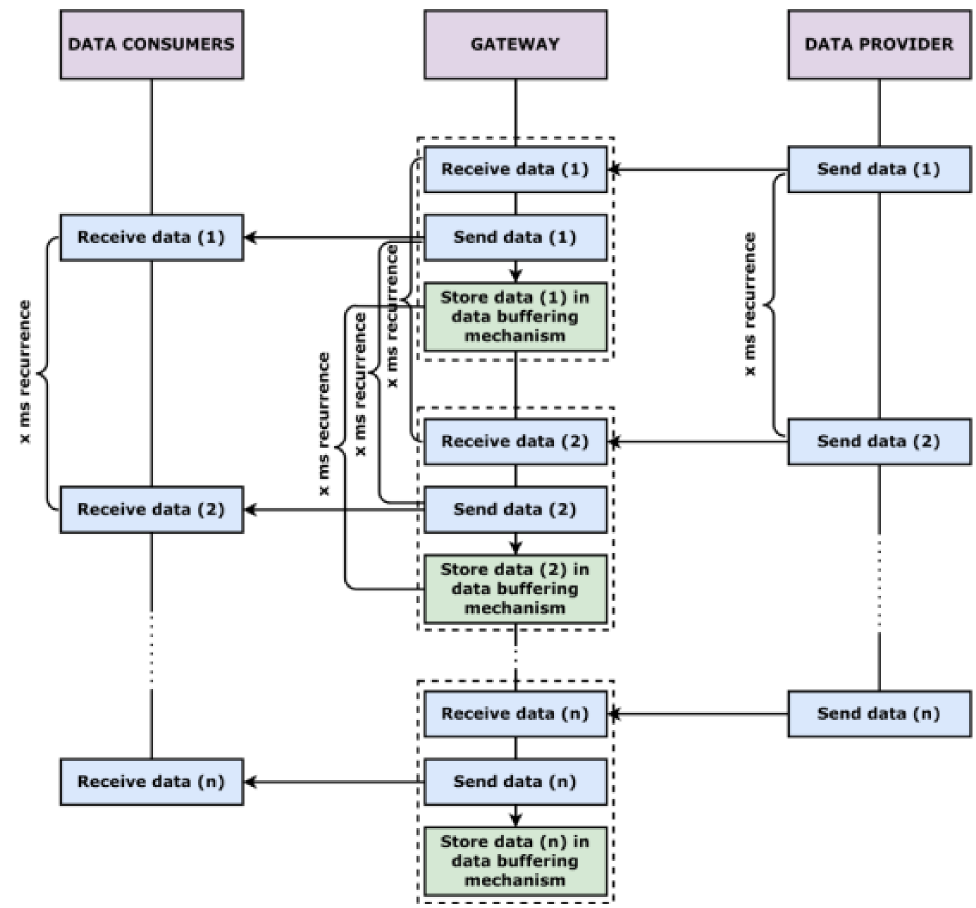


Figure 29. Data buffering sequence

6.3. Results

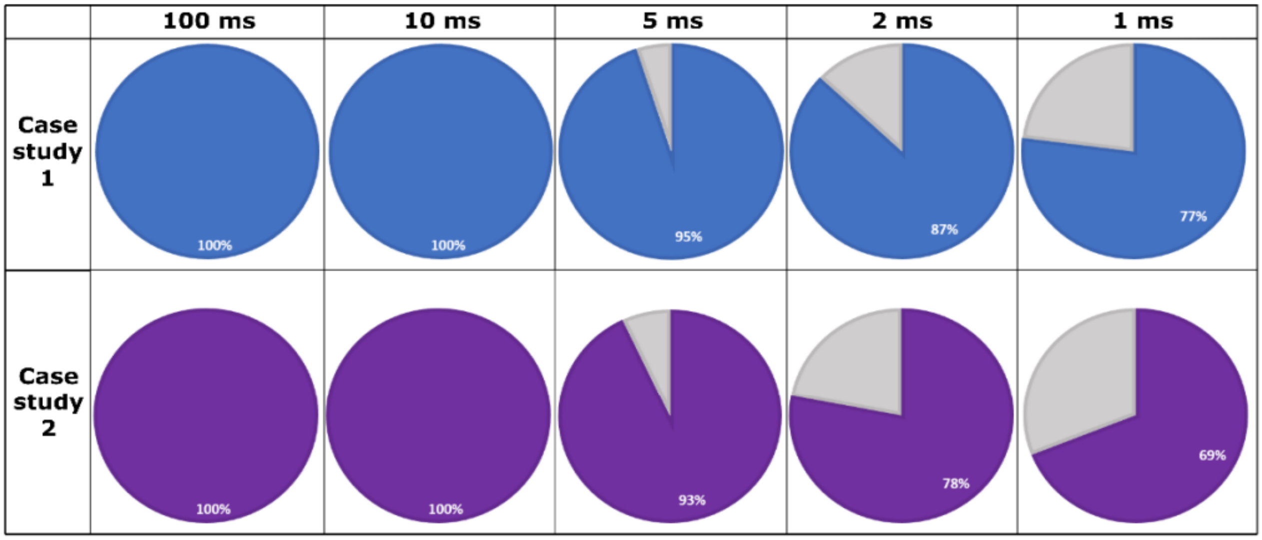


Figure 30. Data buffering success rate results. Data buffering success rate result

The obtained results confirm the compatibility of the concept with different designs for the gateway application and with different roles assigned to the nodes of the architecture. The data buffering subcomponent alongside the signal generator subcomponent of the gateway application allowed a clear observation regarding the efficiency and reliability of the system event in the case of a different data provider and consumers. The results concern the behavior of the communication infrastructure considering real-time requirements and the impact that the network can have on the delivery of messages at fast recurrences. As expected, the efficiency of receiving and transmitting procedures decreased at high recurrences, some of the messages being lost due to network delays. The time intervals selected for observation aimed to highlight the regress from an almost certain transmission of the event, to 1 ms transmission cycles, considered a reasonable performance for the current system. Another contributing factor to less accurate transmissions is the inability of the general usage operating systems to handle operations under 10 ms and to assure the necessary responsiveness for hard real-time requirements.

When discussing the efficiency of an Ethernet-based communication system, without dedicated standards and protocols in place, for assuring that the devices are synchronized over a common time base and each one can deliver the data accordingly to the hard real-time requirements, there are no guarantees that the transmission will be constantly performed in the desired time frame. The current results prove the efficiency of Ethernet-based communication between multiple field devices, highlight the limits of a complex system, and validate the compatibility of the protocols and the architecture by applying industrial principles from automotive and IoT fields. The interaction between various already-established technologies and architectures from different domains will be unavoidable, meaning that many challenges will derive from compatibility and efficiency issues. Identifying suitable communication protocols and architectural designs alongside limitations and improvement directions for expanding the applicability of present industrial concepts will produce reliable and scalable applications for future industrial interoperability use-cases.

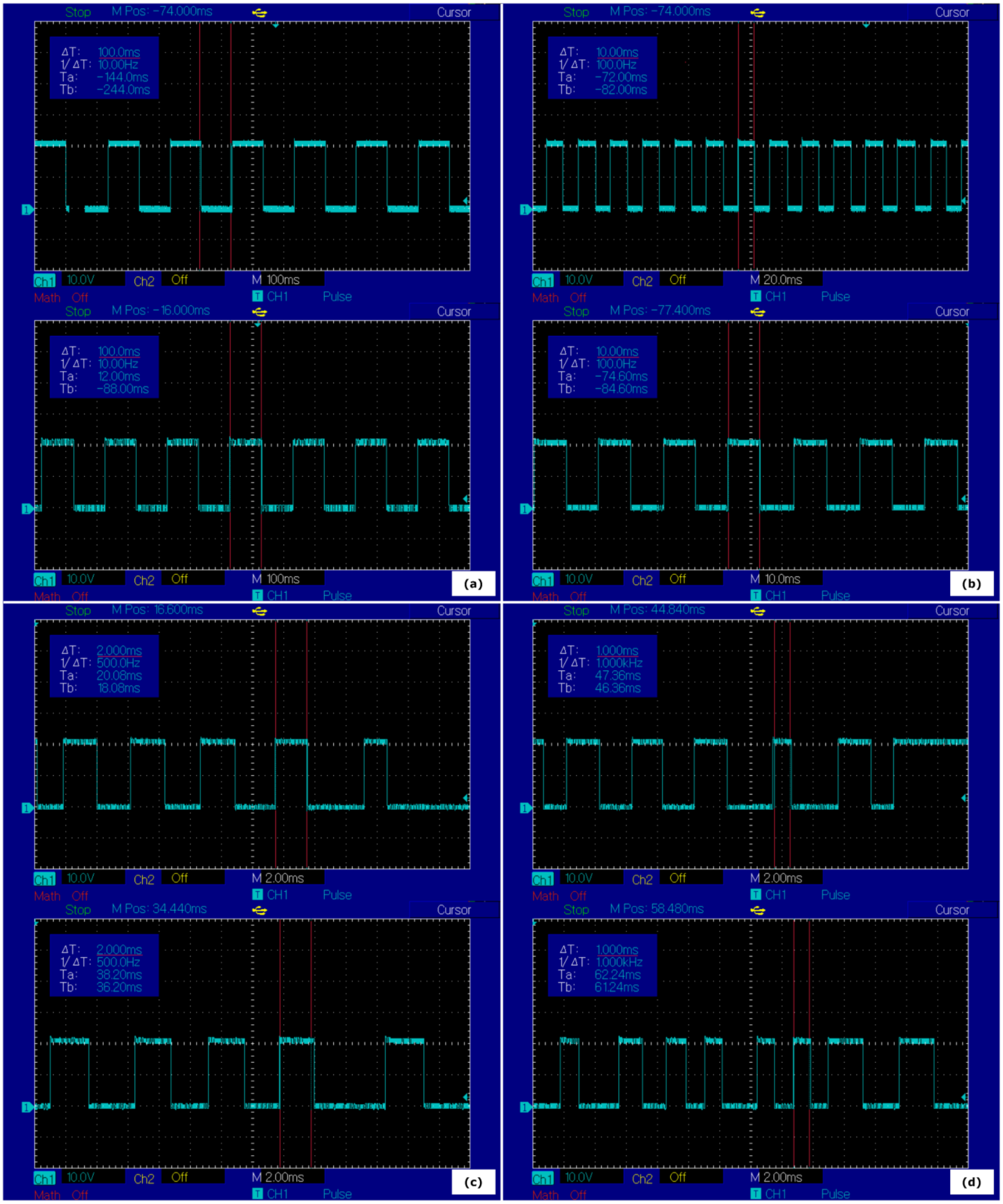


Figure 31. Generated digital signal based on the heartbeat event received and transmitted by the gateway application for case study 1 (above) and case study 2 (below) at (a) 100 ms; (b) 10 ms; (c) 2 ms; (d) 1 ms

With all the current work objectives accomplished, a closer examination is necessary regarding what are the most important conclusions alongside an analysis for the involved technologies and for the importance of the concept for the industry. The multi-protocol gateway managed to interface SOME/IP, DDS, and eCAL entities successfully, considering efficiency and reliability criteria and mapping the concept to a V2X communication scenario. The defined architecture was suitable for the interaction between three different communication technologies in two case studies, each one based on a different version of the gateway and with significant particularities. The results regarding the real-time behavior allowed a better understanding of the challenges concerning Ethernet communication in the context of IoT, and the methods and strategies used for generating the results can be applied at a larger scale, offering clear improvement paths. The compatibility of SOME/IP, DDS, and eCAL has been confirmed, offering an overview of the perspectives in different industrial domains and identifying certain advantages and disadvantages related to each protocol, as shown in Table 10.

Table 10. Advantages and disadvantages related to SOME/IP, DDS, and eCAL

Protocol	Advantages	Disadvantages
SOME/IP	• AUTOSAR-compliant • Validated in multiple automotive use-cases • Supported on both classic and adaptive platforms • Reliable and efficient	• Complex configuration process
DDS	• AUTOSAR-compliant • Offers multiple mechanisms that assure flexibility and scalability • Supported on adaptive platform • Validated in multiple IoT applications and use-cases	• Not established in the automotive domain, despite being AUTOSAR-compliant
eCAL	• Efficient, intuitive, and easy to use for Ethernet communication scenarios • Easy configuration process • High potential for industrial and automotive-related use-cases	• Not AUTOSAR-compliant for now • Not very known • Not applied to full potential in explicit technical areas

Based on the current study and on the industrial context, it is clear that SOME/IP represents a reliable and efficient solution for Ethernet communication, being supported by the AUTOSAR standard and widely present in automotive applications. Being complex and suitable for multiple scenarios, the configuration process requires time and effort especially in complex SOAs, as was also concluded in the current work when compared to an IoT protocol. DDS is becoming more present in IoT industrial systems and its mechanisms offer increased flexibility and scalability. The AUTOSAR compliance also makes it suitable for automotive applications, and although for now it is not established, any possible interactions with the SOME/IP middleware in an automotive-related context represents a high interest topic of research. The eCAL middleware is not very known, but nevertheless, it offers an easy-to-use and intuitive alternative for Ethernet message delivery. Its potential is not fully determined, so the interaction with other middleware solutions will contribute to a better understanding of how it can be applied.

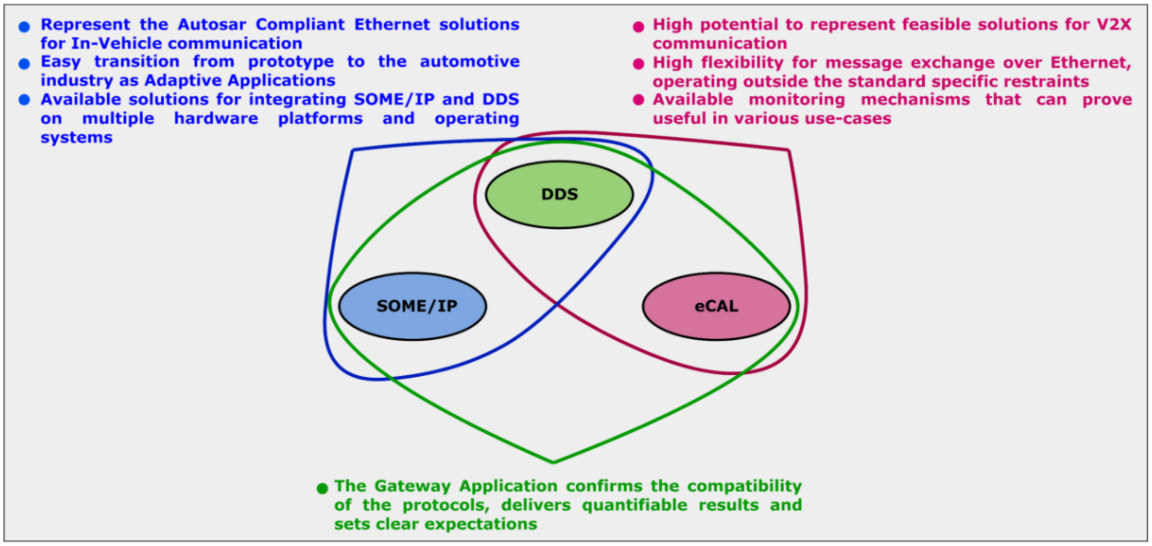


Figure 32. An overview of the utilized technologies

The Ethernet-based communication structures represent the foundation of the concept, with efficiency and reliability under any circumstances being major objectives for any long-term solutions. The validated communication protocols offer multiple designated mechanisms for achieving the needs of the industry and are well established in particular industrial domains. The concept is relevant for automotive and IoT domains by taking into account trends and strategies of high significance from industrial and academic perspectives.

7. PERSONAL CONTRIBUTIONS

Based on the objectives established for the current doctoral research, this section enumerates the author's personal contributions, recorded during all the stages of the research, as follows:

- Conducting a research corelated to the field and topic of the current thesis, identifying clear development directions, relevant to multiple industry sectors.
- A practical implementation of a multi-version structured gateway application between OPC UA and SOME/IP in the context of a Car-to-Infrastructure communication scenario.
- An analysis regarding the TSN technology, identifying the benefits and potential impact, in the case of the implementations developed for each research phase.
- Improving the OPC UA Publish-Subscribe mechanism from an architectural point of view, in the context of real-time performance, providing a detailed insight regarding the available implementations based on the Publish-Subscribe paradigm.
- Extending the applicability of the OPC UA protocol by using the Publish-Subscribe mechanism for image transmission, exploring the capabilities to handle large data volumes.
- The implementation of a DDS - OPC UA gateway application, analyzing the coexistence of the two technologies in a common and parallel context, within an architecture defined in accordance with industrial principles.
- Define relevant and scalable criteria and methods for identifying real-time operating limits for complex Ethernet communication systems
- The development of a multi-protocol gateway solution facilitating interoperability between SOME/IP, DDS and eCAL in the context of a V2X communication scenario, analyzing and combining automotive and IoT specific technologies.
- Definition of numerous complex architectures incorporating diverse technologies and devices in accordance with industrial principles and requirements.
- Achievement of quantifiable results that show the current capabilities of communication and interoperability systems, both in terms of efficiency and stability, thus increasing the use of relevant technologies in new industrial situations and processes.

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