UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Escuela Técnica Superior de Ingeniería de Telecomunicación

Definición, diseño, implementación y validación de un gemelo digital de redes 5G orientado a dar servicios para la Industria 4.0.

Trabajo Fin de Máster

Máster Universitario en Ingeniería de Telecomunicación

AUTOR/A: Cañete Martín, Jorge

Tutor/a: Palau Salvador, Carlos Enrique

Cotutor/a externo: LUCAS ESTAÑ, MARIA DEL CARMEN

CURSO ACADÉMICO: 2023/2024

Abstract

The main goal of this Master's Thesis is the definition, design, implementation, and validation of a Digital Twin or Asset Administration Shell (AAS) for 5G networks aimed at providing services for Industrie 4.0. A Digital Twin try to make a digital representation of a physical object called an Asset. Digital twins use is on the rise in the Industriy to have digital models of physical processes that allow for more agile optimization of production processes. It is expected that these processes will use 5G networks, so it is necessary for the digital twins of production plants to integrate digital twins of 5G networks.

Another objective of this Master's Thesis is to generate a digital twin of the 5G network that should model relevant information about the 5G network as well as its main functions. The definition of the 5G AAS will be carried out mainly following the guidelines and standards of Industrie 4.0 Platform (Germany), 5G-ACIA, and the 3GPP. Industrie 4.0 Platform has proposed standards and models for the definition of AASs, while 5G-ACIA has defined at a high level how 5G AAS should be applied to Industrie 4.0. Finally, it is necessary to develop a 5G digital twin in accordance with the standards defined by the 3GPP.

As specified by 5G-ACIA, the 5G AAS is composed of 2 main AASs: the 5G UE and the 5G network. This Master's Thesis focuses on the definition of the 5G network AAS. The 5G Network will encompass 5G Network information, including the radio and core network parts. The definition will be approached in different phases: a first phase covering the essential QoS functions of the 5G Network through a passive AAS, a second phase focusing on active functions or behaviors where the AAS will have the ability to interact with other AAS, and a last phase where the main network functions will be added. To facilitate the interaction/integration of the 5G AAS with the digital model of the industrial plant covered by the network, the necessary interfaces will be implemented.

This professionally-oriented Master's Thesis have been carried out at Miguel Hernández University in Elche, in the Uwicore laboratory.

Resumen

Este TFM tiene por objetivo la definición, diseño, implementación y validación de un gemelo digital (Digital Twin) o Asset Administration Shell (AAS) de redes 5G orientado a dar servicios para la Industria 4.0. Un gemelo digital busca la representación digital de un objeto físico al que se denomina Asset. El uso de gemelos digitales está en auge en la industria con el fin de disponer de modelos digitales de los procesos físicos que permitan una más ágil optimización de los procesos de producción. Está previsto que dichos procesos utilicen las redes 5G, y es por tanto necesario que los gemelos digitales de las plantas de producción integren gemelos digitales de las redes 5G.

El objetivo de este TFM es generar un gemelo digital de la red 5G que deberá modelar la información relevante de la red 5G así como sus principales funciones. La definición del 5G AAS se realizará siguiendo principalmente las indicaciones y estándares de Industrie 4.0 Platform (Alemania), 5G-ACIA y el 3GPP. Industrie 4.0 Platform ha propuesto estándares y modelos para la definición de AASs, mientras que 5G-ACIA ha definido a alto nivel como deben ser los AAS 5G aplicados a la industria 4.0. Por último, es necesario desarrollar un gemelo digital 5G acorde a los estándares definidos por el 3GPP.

Según establece 5G-ACIA, el 5G AAS está compuesto por 2 AASs principales: el 5G UE y el 5G network. Este TFM se centra en la definición del 5G network AAS. El 5G Network englobará toda la información de esa red 5G, incluyendo la parte de radio y el core network. La definición se abordará en distintas fases, una primera fase en la que cubriremos las funciones esenciales de QoS del 5G Network mediante un AAS pasivo, una segunda donde nos centraremos en funciones o comportamientos activos en los que el AAS tendrá la capacidad de interactuar con otros AAS, y una última fase donde se añadirán las principales funciones de red. Con el fin de facilitar la interacción/integración del 5G AAS con el modelo digital de la planta industrial a la que la red da cobertura, se trabajará en la implementación de las interfaces necesarias.

Este TFM de carácter profesional ha sido realizado en la Universidad Miguel Hernández de Elche, en el laboratorio Uwicore.

Resum

L'objectiu d'aquest Treball de Fi de Màster és la definició, disseny, implementació i validació d'un bessó digital o closa d'administració d'actius (AAS) per a xarxes 5G amb l'objectiu de proporcionar serveis per a la Indústria 4.0. Un bessó digital és una representació digital d'un objecte físic anomenat actiu. L'ús de bessons digitals està en auge en la indústria per tenir models digitals de processos físics que permetin una optimització més àgil dels processos de producció. Es preveu que aquests processos utilitzen les xarxes 5G, pel que és necessari que els bessons digitals de les plantes de producció integren bessons digitals de les xarxes 5G.

L'objectiu d'aquest Treball de Fi de Màster és generar un bessó digital de la xarxa 5G que haurà de modelar la informació rellevant de la xarxa 5G així com les seves principals funcions. La definició del 5G AAS es realitzarà principalment seguint les indicacions i estàndards de la Plataforma Industrie 4.0 (Alemanya), 5G-ACIA i el 3GPP. La Plataforma Industrie 4.0 ha proposat estàndards i models per a la definició de AAS, mentre que 5G-ACIA ha definit a nivell alt com han de ser els AAS 5G aplicats a la indústria 4.0. Finalment, és necessari desenvolupar un bessó digital 5G d'acord amb els estàndards definits pel 3GPP.

Segons establix 5G-ACIA, el 5G AAS està compost per 2 AAS principals: el 5G UE i el 5G network. Aquest Treball de Fi de Màster se centra en la definició del 5G network AAS. La xarxa 5G englobarà tota la informació d'aquesta xarxa 5G, incloent la part de ràdio i el core network. La definició es durà a terme en diferents fases: una primera fase en què cobrirem les funcions essencials de QoS del 5G Network mitjançant un AAS passiu, una segona on ens centrarem en funcions o comportaments actius en què l'AAS tindrà la capacitat d'interactuar amb altres AAS, i una última fase on s'afegiran les principals funcions de xarxa. Amb l'objectiu de facilitar la interacció/integració del 5G AAS amb el model digital de la planta industrial a la qual la xarxa dóna cobertura, es treballarà en la implementació de les interfícies necessàries.

Aquest Treball de Fi de Màster de caràcter professional ha sigut realitzat a la Universitat Miguel Hernández d'Elx, en el laboratori Uwicore.

ACKNOWLEDGMENT

I would like to extend my heartfelt gratitude to several individuals from Uwicore who have contributed to the completion of this thesis.

First and foremost, I am deeply thankful to my colleague, Jorge Gomez, whose insights and collaboration were invaluable throughout this journey. His dedication and support have truly enriched the quality of this work. I am also indebted to my esteemed superiors, Mari Carmen Lucas, Javier Gozalvez and also to my thesis advisor Carlos Palau, for their guidance, encouragement, and unwavering belief in my abilities. Their mentorship has been instrumental in shaping the direction of this research. Additionally, I wish to express my appreciation to Eloy Gonzalez for his assistance and encouragement at various stages of this project.

Lastly, I am grateful to all those who have supported me directly or indirectly during this endeavor. Your encouragement and belief in my capabilities have been instrumental in bringing this thesis to fruition. Thank you all for your invaluable contributions and unwavering support.

FUNDING

This work has been funded by European Union's Horizon Europe Research and Innovation programme under the Re4dy project (No 101058384).

SUBMITTED PUBLICATIONS

J. Gómez-Jerez, J. Cañete-Martín, M.C. Lucas-Estañ, J. Gozalvez, "5G UE and Network Asset Administration Shells for the Integration of 5G and Industry 4.0 Systems", submitted to *IEEE International Conference on Emerging Technologies and Factory Automation (IEEE ETFA 2024)*, 10-13 Sept. 2024, Padova, Italy.

J. Gómez-Jerez, J. Cañete-Martín, M.C. Lucas-Estañ, J. Gozalvez, "Integration of 5G into Digital Models of Industrial Production Plants", submitted to *IEEE International Conference on Emerging Technologies and Factory Automation (IEEE ETFA 2024)*, 10-13 Sept. 2024, Padova, Italy.

RESUMEN EJECUTIVO

La memoria del TFM del Máster Universitario en Ingeniería de Telecomunicación debe desarrollar en el texto los siguientes conceptos, debidamente justificados y discutidos, centrados en el ámbito de la ingeniería de telecomunicación

CONCEPT (ABET)	**CONCEPTO (traducción)**	**¿Cumple? (S/N)**	**¿Dónde? (páginas)**
1. IDENTIFY:	1. IDENTIFICAR:		
1.1. Problem statement and opportunity	1.1. Planteamiento del problema y oportunidad	S	1
1.2. Constraints (standards, codes, needs, requirements & specifications)	1.2. Toma en consideración de los condicionantes (normas técnicas y regulación, necesidades, requisitos y especificaciones)	S	4-7
1.3. Setting of goals	1.3. Establecimiento de objetivos	S	1
2. FORMULATE:	2. FORMULAR:		
2.1. Creative solution generation (analysis)	2.1. Generación de soluciones creativas (análisis)	S	10-30
2.2. Evaluation of multiple solutions and decision-making (synthesis)	2.2. Evaluación de múltiples soluciones y toma de decisiones (síntesis)	S	32-41
3. SOLVE:	3. RESOLVER:		
3.1. Fulfilment of goals	3.1. Evaluación del cumplimiento de objetivos	S	36-41
3.2. Overall impact and significance (contributions and practical recommendations)	3.2. Evaluación del impacto global y alcance (contribuciones y recomendaciones prácticas)	S	41

Index

List of Figures

List of Tables

1. Introduction

1.1 Motivation

The profound evolution witnessed in recent years within the Industrie 4.0 landscape has sparked a compelling motivation to embark upon this project. This transformational journey has not only redefined traditional manufacturing and automation paradigms but has also heralded the dawn of a new era marked by interconnected systems, autonomous decision-making processes, and data-centric operations. As industries worldwide grapple with the complexities of this paradigm shift, there arises an imperative to harness the transformative potential of emerging technologies, particularly in the realms of asset management and wireless communications.

At the core of this motivation lies the recognition of the pivotal role played by effective asset management in driving operational excellence within industrial ecosystems. The advent of Asset Administration Shells (AAS) as standardized digital representations of physical assets represents a watershed moment in this journey towards optimization and efficiency. By encapsulating the properties, behaviors, and interrelationships of assets within a digital twin framework, AAS empowers organizations to streamline operations, enhance productivity, and unlock new avenues for innovation.

Moreover, the integration of 5G Wireless Communications stands as a cornerstone development within this narrative. With its promise of low latency and high bandwidth, 5G technology has the potential to revolutionize industrial operations. The abstracts provided elucidate the paramount importance of integrating 5G technology via AAS for enhanced industrial connectivity and performance. They underscore the need for an explanation of 5G systems following AAS principles, offering a simplified interface to help industry professionals work with 5G systems, thereby driving innovation, efficiency, and competitiveness in the manufacturing landscape.

As organizations strive to remain agile and competitive in an increasingly digitized landscape, the deployment of 5G networks emerges as a strategic imperative, unlocking new avenues for innovation, efficiency, and competitiveness. By leveraging the synergies between AAS, Digital Twins, and 5G networks, organizations can unlock new possibilities for advanced monitoring, simulation, and optimization, thereby driving continuous improvement and resilience in manufacturing processes. It is within this context of transformative potential and imperative collaboration that the motivation for undertaking this project emerges.

1.2 Objective

The objectives of this project are twofold, aimed at advancing the understanding and practical implementation of 5G technology integrated via AAS within the Industrie 4.0 framework.

Firstly, this project aims to propose a comprehensive framework for the deployment of 5G AAS within industrial environments. By delving into specific use cases outlined by the 5G-ACIA and elucidating the practical implications of 5G technology in industrial automation, we aim to contribute to transformative advancements in manufacturing processes. This includes a focused exploration of 5G AAS, encompassing its constituent elements: the 5G User Equipment AAS (5G UE AAS) and the 5G Network AAS (5G NW AAS). By delineating the key components, functionalities, and implementation strategies of 5G AAS, we seek to provide organizations with a structured approach to harnessing the transformative potential of 5G technology.

Secondly, this project endeavors to explore specific use cases and applications that demonstrate the practical implications of 5G technology in enhancing connectivity, efficiency, and agility in manufacturing and automation processes. Leveraging insights from industry best practices and real-world scenarios, we aim to elucidate the tangible benefits of 5G AAS in optimizing operational workflows, accelerating decision-making processes, and unlocking new levels of productivity. Through the exploration of use cases such as connection/disconnection to/from the 5G Network Public Network (NPN), periodically reported location information, and movement events, we seek to provide industry professionals with actionable insights into the transformative potential of 5G technology in industrial settings.

By achieving these objectives, we aim to contribute to the ongoing digital transformation of industrial operations, aiming innovation, efficiency, and sustainability in the Industrie 4.0 era. It is our endeavor to provide organizations with the knowledge and tools necessary to navigate the complexities of integrating 5G technology via AAS, thereby unlocking new avenues for growth and competitiveness in the manufacturing landscape.

1.3 Structure

The project memory will consist of 7 chapters:

- Chapter 1: The primary motivation behind developing this master's thesis and the main as well as secondary objectives are elucidated.
- Chapter 2: Concepts and standards underpinning Asset Administration Shells are introduced.
- Chapter 3: The integration of Asset Administration Shells with 5G networks is explored, along with our proposed model for the 5G Network AAS.
- Chapter 4: The communication interface developed for Asset Administration Shells is described.
- Chapter 5: Visual Components, the software used to simulate the industrial environment communicating through our Asset Administration Shells, is introduced. The results obtained from various simulations are analyzed.
- Chapter 6: Conclusions and future lines drawn from the development of the master's thesis are presented.
- Chapter 7: Bibliography.

2. Asset Administration Shell theoretical framework

2.1 Introduction

This chapter delves into the theoretical framework of AAS, exploring its types, specifications, and the crucial role it plays in the intelligent networking of machinery and processes. By examining the structure, communication protocols, and practical applications of AAS, we aim to highlight its significance in driving operational excellence and innovation within Industrie 4.0.

AAS is a very important concept within the framework of Industrie 4.0, offering standardized digital representations of assets to facilitate interoperability and efficient asset management in manufacturing environments. As a cornerstone of Industrie 4.0, AAS serve as virtual interfaces accessible within the manufacturing network, providing comprehensive information and functionalities related to assets.

Within the context of Industrie 4.0, assets encompass both physical and logical entities crucial for organizational operations, including machinery, documents, materials, and software. Effective management of these assets is essential for optimizing performance and driving operational excellence in manufacturing processes. It is important to note that not all information may be accessible across all deployment scenarios.

AAS consists of digital models, or submodels, which describe various aspects of assets, including their features, capabilities, status, and operational data. By encapsulating this information within AAS, organizations can achieve seamless integration and interoperability between different systems and applications managing manufacturing processes. Additionally, AAS facilitates efficient communication between assets and external applications through standardized interfaces, such as APIs, enabling controlled access to asset data and functionalities.

There exist various subcategories within submodel elements aimed at delineating a model for an asset, such as properties, operations, lists, etc. To aid in understanding our AAS proposal, we will elucidate some of these subcategories. Properties covers data submodel element containing a value of a simple type, such as string or date. Submodel Element Lists serve for sets, ordered lists, bags, and ordered sets. Additionally, they facilitate the creation of multidimensional arrays. Submodel Element Collections are used for entities with a fixed set of properties, each possessing unique names within the structure. An operation, on the other hand, is a submodel element encompassing input and output variables, typically delineating the behavior of a component in procedural terms.

In summary, AAS represents a critical component of Industrie 4.0, providing standardized digital representations of assets and serving as a central interface for efficient asset management and interoperability within manufacturing environments. Through the adoption of AAS principles and RAMI 4.0 framework, organizations can streamline asset administration processes, enhance operational efficiency, and unlock new opportunities for innovation and growth in the era of Industrie 4.0.

2.2 Types of AAS

The AAS is divided into two main parts: a passive part and an active part. The passive part refers to properties that does not involve any activity. On the other hand, the active part consists of procedures and algorithms performed by the asset and the AAS. This active part is composed of methods that can be used, for example, to read and write property values in the AAS/asset. Additionally, the active part of an AAS has service-oriented communication capabilities and decision-making functionalities.

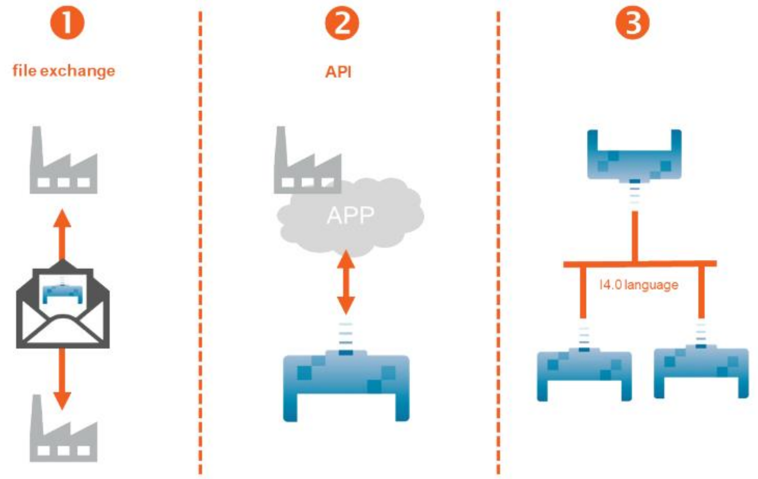


Fig. 1. Types of AAS [1]

As we can see in Fig. 1, Industrie 4.0 differences three types of AAS, they can be passive, reactive, or proactive. As a result of this, the following high-level interaction patterns between AAS instances are distinguished: Type 1 (Passive) interactions involve standardized data structuring for file-based exchange. Type 2 (Reactive) interactions utilize standardized interfaces like REST or Open Platform Communications Unified Architecture (OPC-UA) for asymmetrical vertical interactions. Type 3 (Proactive) interactions enable peer-to-peer communication between Industrie 4.0 components, facilitating proactive system integration and plug & play scenarios. We can use every one of them for:

- A type 1 or passive AAS can only be used to store information of a device, without any activity that can change anything on it. In short, it will be used as a information pool to consult the parameters of the device the AAS is paired with. Normally the AAS acts as a static file or file package.
- A type 2 or reactive AAS can have some behaviours and communicate through some APIs depending on some events that could trigger a communication with other AAS or with an external software.
- A type 3 or active AAS communicates in an autonomous form which others of the same type, this communication is made by Industrie 4.0 language defined by [2]. Through this language, AAS can cooperate and understand each other.

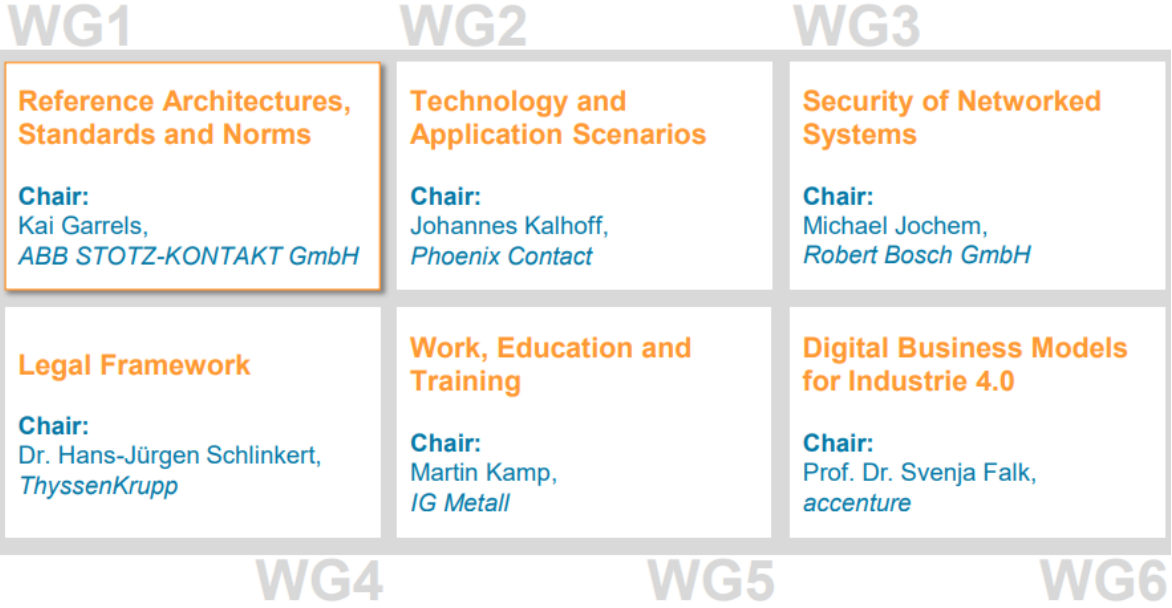
The defined 5G UE and NW AASs correspond to type 2 or reactive AASs that include both passive data and active functions. Furthermore, the defined AASs will have the capability of interfacing with other AASs and software applications via APIs (implemented using OPC-UA). The passive version of the defined 5G UE and NW AASs has been implemented using the AASX Package Explorer application which is a standardized open-source tool designed for creating and managing AAS. The complete active version of the AASs is implemented in Basyx. Both passive and active versions of the 5G UE and NW AASs is openly available at [3].

2.3 AAS specification

Industrie 4.0 encompasses the intelligent networking of machinery and processes within the industrial domain, facilitated by advancements in information and communication technology. Firms employ this intelligent networking paradigm in diverse manners, including the facilitation of flexible production, optimization of workflows, utilization of data analytics, and promotion of resource-efficient practices.

Industrie 4.0 is actively engaged in the development of AAS and has established robust standards governing their implementation. These standards encompass various documents that delineate the intricacies of AAS across different domains. Among these documents, one of the most notable series is titled "Details of Asset Administration Shell," which is segmented into several parts, each addressing specific aspects of AAS. Predominantly, our focus has been on Part 1, which elucidates the AAS metamodel, and Part 2, which delves into communication protocols, as we shall elucidate in subsequent sections. Additionally, Part 3 [4] provides specifications for data representation, while Part 5 [5] defines the file format for AAS, denoted by the extension. aasx.

This organizational endeavor is subdivided into distinct working groups, each tasked with overseeing specific facets of AAS technology. As depicted in Fig. 2, the working groups are delineated according to the fields they address, with designated leaders responsible for guiding each group efforts.



WG1

Reference Architectures, Standards and Norms

Chair:
Kai Garrels,
ABB STOTZ-KONTAKT GmbH

WG2

Technology and Application Scenarios

Chair:
Johannes Kalhoff,
Phoenix Contact

WG3

Security of Networked Systems

Chair:
Michael Jochem,
Robert Bosch GmbH

WG4

Legal Framework

Chair:
Dr. Hans-Jürgen Schlinkert,
ThyssenKrupp

WG5

Work, Education and Training

Chair:
Martin Kamp,
IG Metall

WG6

Digital Business Models for Industrie 4.0

Chair:
Prof. Dr. Svenja Falk,
accenture

Fig. 2. Industrie 4.0 Working Groups [6]

2.3.1 AAS metamodel

The objective of [6] is to establish a standardized structure for the AAS, facilitating the seamless exchange of information among assets and other components within the Industrie 4.0 ecosystem. This document primarily focuses on delineating the metamodel of the AAS, including its submodels, mandatory and optional identifiers, and guidelines for encapsulating information to enable interoperability. Furthermore, it addresses standardized mappings for translating AAS information into XML or JSON formats, ensuring compatibility across different systems and platforms.

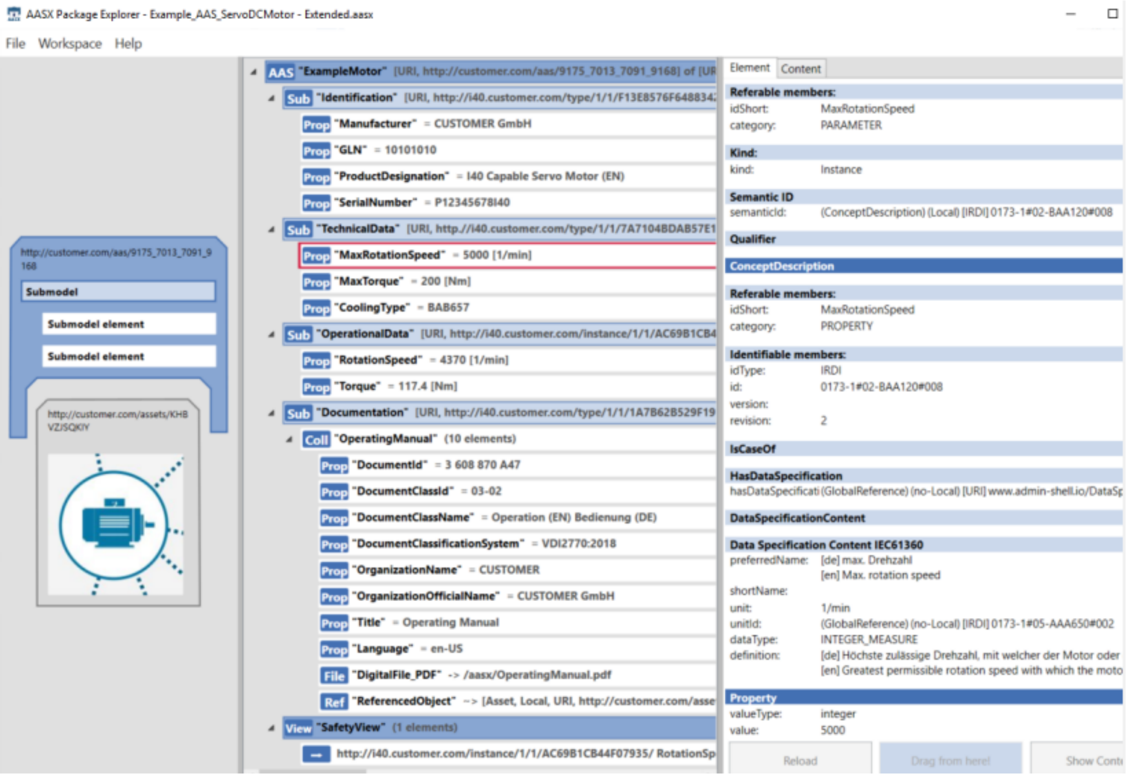
According to this document, several prerequisites must be met for the exchange of AAS information between different partners:

- Definition of the AAS in the required format, typically with a. aasx extension, although XML or JSON formats may be acceptable in certain implementations.
- Inclusion of additional files that may be referenced in the submodels.
- Establishment of a secure method for file exchange, such as a server.

The structure of the AAS adheres to a consistent core hierarchy, as illustrated in Fig. 3. At its core is the AAS, serving as the standardized digital representation of the physical assets within the industry. The AAS contains digital models of various domains, referred to as submodels, which encapsulate identification, behavior, and other aspects of the assets. Each submodel comprises different types of elements that encompass the information relevant to its domain:

- Capability attributes: Descriptions of an asset's potential to accomplish specific tasks in the physical or digital realms.
- Data elements: Submodel elements that cannot be composed of other submodel elements.
- Operation attributes: Definitions of submodel elements with input and output variables.
- Concept description attributes: Additional information associated with elements to address misconceptions or provide insights into properties or submodels.
- Properties: Characteristics suitable for describing and distinguishing products or components.
- Files: Submodel elements containing references to supplementary files complementing the AAS information.

Industrie 4.0 has standardized a tool for creating AAS models in the. aasx format, known as the AASX Package Explorer. This software, available for download from [7], facilitates the creation of AAS models while ensuring adherence to the metamodel outlined in the document. Any deviations from the specified rules are flagged by the software to ensure compliance with Industrie 4.0 requirements. An example model created using the AASX Package Explorer illustrates an AAS with its various submodels, each containing elements of different types.



```
AAS "ExampleMotor" [URI, http://customer.com/aas/9175_7013_7091_9168] of [UR
  Sub "Identification" [URI, http://i40.customer.com/type/1/1/F13E8576F648834
    Prop "Manufacturer" = CUSTOMER GmbH
    Prop "GLN" = 10101010
    Prop "ProductDesignation" = I40 Capable Servo Motor (EN)
    Prop "SerialNumber" = P12345678I40
  Sub "TechnicalData" [URI, http://i40.customer.com/type/1/1/7A7104BDAB57E1
    Prop "MaxRotationSpeed" = 5000 [1/min]
    Prop "MaxTorque" = 200 [Nm]
    Prop "CoolingType" = BAB657
  Sub "OperationalData" [URI, http://i40.customer.com/instance/1/1/AC69B1CB4
    Prop "RotationSpeed" = 4370 [1/min]
    Prop "Torque" = 117.4 [Nm]
  Sub "Documentation" [URI, http://i40.customer.com/type/1/1/1A7B62B529F19
    Coll "OperatingManual" (10 elements)
      Prop "DocumentId" = 3 608 870 A47
      Prop "DocumentClassId" = 03-02
      Prop "DocumentClassName" = Operation (EN) Bedienung (DE)
      Prop "DocumentClassificationSystem" = VDI2770:2018
      Prop "OrganizationName" = CUSTOMER
      Prop "OrganizationOfficialName" = CUSTOMER GmbH
      Prop "Title" = Operating Manual
      Prop "Language" = en-US
      File "DigitalFile_PDF" -> /aasx/OperatingManual.pdf
      Ref "ReferencedObject" ~> [Asset, Local, URI, http://customer.com/asse
  View "SafetyView" (1 elements)
    → http://i40.customer.com/instance/1/1/AC69B1CB44F07935/ RotationSp
```

```
Referable members:
idShort:        MaxRotationSpeed
category:       PARAMETER

Kind:
kind:           Instance

Semantic ID
semanticId:     (ConceptDescription) (Local) [IRDI] 0173-1#02-BAA120#008

Qualifier

ConceptDescription

Referable members:
idShort:        MaxRotationSpeed
category:       PROPERTY

Identifiable members:
idType:         IRDI
id:             0173-1#02-BAA120#008
version:
revision:       2

IsCaseOf

HasDataSpecification
hasDataSpecificati (GlobalReference) (no-Local) [URI] www.admin-shell.io/DataSp

DataSpecificationContent

Data Specification Content IEC61360
preferredName:  [de] max. Drehzahl
                [en] Max. rotation speed
shortName:
unit:           1/min
unitId:         (GlobalReference) (no-Local) [IRDI] 0173-1#05-AAA650#002
dataType:       INTEGER_MEASURE
definition:     [de] Höchste zulässige Drehzahl, mit welcher der Motor oder
                [en] Greatest permissible rotation speed with which the moto

Property
valueType:      integer
value:          5000
```

Fig. 3. AAS model in AASX Package Explorer [7]

In Fig. 3, a notable aspect is the data types stored by properties, which mirror the typical data types found in programming languages, such as integers, doubles or floats, strings, booleans, and more complex data types like dates. This document provides a comprehensive explanation of all data types usable in AAS technology.

Additionally, the document introduces identifiers, emphasizing the need for every AAS, asset, submodel, or property to have a unique identifier, as depicted in Fig. 4. While elements can sometimes be identified using their idshort or public name, these may not always be unique or detailed enough for identification purposes. Identifiers serve two main purposes: to distinguish all elements of an Administration Shell and the assets they represent, and to relate elements to external definitions. Three types of identifiers are outlined:

1. IRDI: Utilized as an identifier scheme for properties and classifications, following standards such as ISO 29002-5, ISO IEC 6523, and ISO IEC 11179-6. IRDIs are established through consortium-wide specifications or international standardization processes.
2. IRI or URI and URL: Employed for the identification of assets, Administration Shells, and other properties and classifications. While not necessarily standardized, these identifiers, compliant with RFC 3986, ensure global uniqueness.
3. Custom: Internal custom identifiers like UUIDs/GUIDs (globally unique identifiers/universally unique identifiers), which manufacturers may use for various in-house purposes within the Administration Shell.

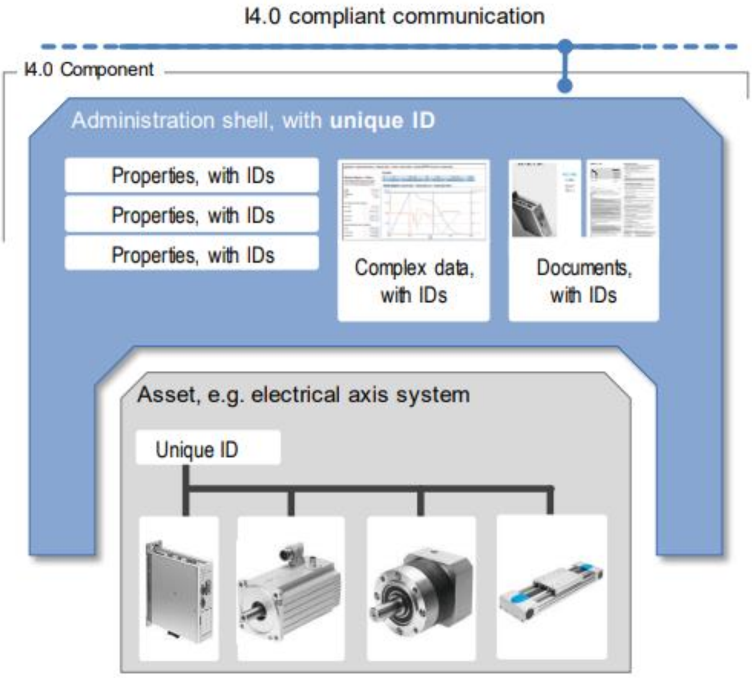


Fig. 4. Identifiers across the AAS [6]

2.3.2 AAS communication

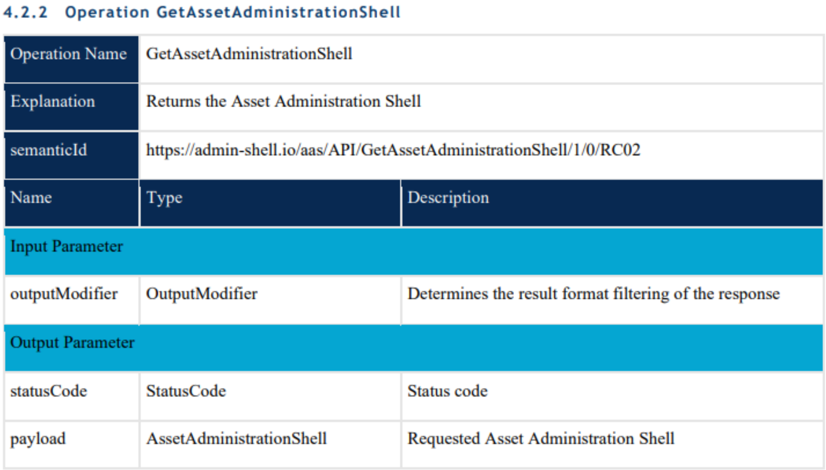
[8] elaborates on the interfaces and APIs for the AAS and its submodels. While Part 1 outlined the information of the AAS to be exchanged, Part 2 elucidates the APIs enabling online access to the information provided by the AAS. The operational principles of the interfaces closely adhere to general REST principles.

These principles include:

1. **Clearly Defined Nouns**: Every resource involved in an operation should have a clearly defined noun, with relations specified as outlined in Part 1.
2. **Functionality of REST Methods**: The operations align with the functionality of REST methods. The primary operations include:
    - **GET**: Retrieves a single resource based on the provided identifier.
    - **POST**: Creates a new resource with the given parameters as operation arguments.
    - **PUT**: Updates the value of an existing resource.
    - **DELETE**: Removes the resource specified by the identifier.

While there are additional operations, these are the main ones used. These methods can be applied to various parts of the AAS, such as the entire AAS, a complete submodel, or an individual submodel element (often a property).

In Fig. 5, an example of a GET method applied to the entire AAS is illustrated. In this scenario, the desired AAS is specified as input, and the response includes a Status Code and payload. The Status Code indicates the result of the operation, with 200 signifying success, 400 indicating incorrect parameters, and 404 indicating a server not found error. The payload typically contains the entire AAS, presented as either an object or a serialized form, depending on the API used.

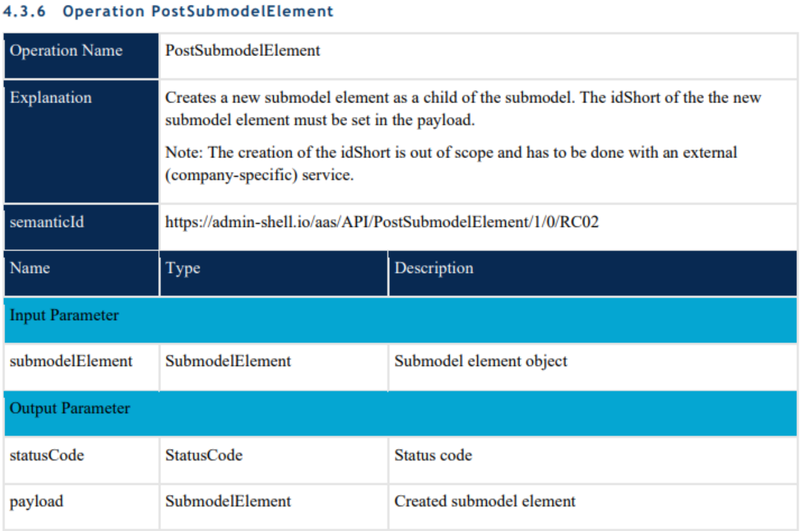


4.2.2 Operation GetAssetAdministrationShell

Operation Name	GetAssetAdministrationShell	
Explanation	Returns the Asset Administration Shell	
semanticId	https://admin-shell.io/aas/API/GetAssetAdministrationShell/1/0/RC02	
Name	Type	Description
Input Parameter		
outputModifier	OutputModifier	Determines the result format filtering of the response
Output Parameter		
statusCode	StatusCode	Status code
payload	AssetAdministrationShell	Requested Asset Administration Shell

Fig. 5. GetAAS method [8]

In Fig. 6, a POST operation is depicted being performed on a submodel element. This operation accepts information about the submodel element, such as its idshort or name, and its corresponding value as arguments. The response from this operation provides the status of the operation. Fig. 5 and Fig. 6 showcase the versatility of this operation, demonstrating its capability to retrieve information about an AAS and to write information to an existing AAS.



4.3.6 Operation PostSubmodelElement

Operation Name	PostSubmodelElement	
Explanation	Creates a new submodel element as a child of the submodel. The idShort of the the new submodel element must be set in the payload. Note: The creation of the idShort is out of scope and has to be done with an external (company-specific) service.	
semanticId	https://admin-shell.io/aas/API/PostSubmodelElement/1/0/RC02	
Name	Type	Description
Input Parameter		
submodelElement	SubmodelElement	Submodel element object
Output Parameter		
statusCode	StatusCode	Status code
payload	SubmodelElement	Created submodel element

Fig. 6. PostSubmodelElement method [8]

As mentioned earlier, these methods adhere to Hypertext Transfer Protocol (HTTP)/ Representational State Transfer (REST) principles. Industrie 4.0 provides a web demo [9] that allows users to experiment with a variety of these methods on an HTTP demo server [10]. This demo is invaluable for understanding how these methods modify the demo AAS on the server and how to retrieve information from them.

In this demo scenario, the API is based on HTTP/REST, making the server an HTTP server. HTTP/REST servers typically utilize JSON as a serialization language. Therefore, the payload of the response from these methods will always be in JSON format. This means that when executing a GET method on a submodel element, such as a property, the response will contain a JSON text, requiring users to filter through the information to extract relevant data. This process may not be very efficient in certain cases, posing a potential challenge.

In [8], HTTP/REST APIs defines how to be mapped to technology-neutral specification. Future works of this specification are expected to support APIs using other technologies, such as OPC UA and MQTT. While these technologies are recognized as valid communication methods for the AAS, their details are not as extensively outlined as those of the HTTP/REST API in the current standard.

3. 5G AAS proposal

3.1 Introduction

In this chapter, we will align our approach with the 5G ACIA documents and 3GPP standards to integrate 5G systems into Industrie 4.0 environments based on AAS principles. Describing a 5G system using AAS principles is essential for effectively managing and interoperating with assets in the factory of the future.

The concept of 5G AAS, advocated by 5G-ACIA, emphasizes the integration of 5G wireless communication technologies in industrial and automation settings. This involves splitting the 5G AAS into two core components: the 5G UE AAS and the 5G NW AAS. The former represents the endpoint of the 5G link at the device level, aligning with 3GPP standards, while the latter encompasses network functions within the 5G Radio Access Network (RAN) and Core Network (CN). This segmentation enables tailored implementations for improved connectivity and performance optimization in industrial contexts.

A 5G network is inherently complex, comprising various devices and network functions distributed across antennas, baseband processing units, and virtualized IT equipment. Structuring the description of the 5G network as an AAS requires careful consideration of this complexity and the creation of well-defined AAS submodels. Additionally, we explore the potential synergies between 5G connectivity and AAS, highlighting their ability to enhance efficiency and resilience in manufacturing processes. Leveraging industrial 5G systems can strengthen communication infrastructures and support resilience in dynamic production environments. This chapter will be a detailed explanation of the concepts and the models of [11].

In this chapter we will also explain some of the active operations that the AAS are designed for. For the operation management we take advantage of the SEAL tool that will be detailed in the end of this chapter. SEAL Service APIs encompass various service operations, with a focus on essential services such as Location Management and Network Resources Management.

This project collectively advance our understanding and implementation of AAS and Digital Twin concepts within Industrie 4.0. Industrie 4.0 outline the importance of standardized communication protocols, interoperability, and the integration of emerging technologies like 5G to unlock the full potential of digital transformation in industrial settings. Further research and standardization efforts are crucial to address existing gaps and facilitate widespread adoption and seamless integration of these innovative approaches into industrial ecosystems.

It should be clarified that the 5G UE proposal is a work done within the framework of RE4DY. However, explaining the 5G UE is necessary for the understanding of the rest of this thesis, so 5G UE AAS is going to be explained in the next subsection and after that 5G Network AAS will be explained.

3.2 5G UE AAS proposal

One of the aims of this thesis is to propose a 5G UE AAS and elucidate its functionality to support industry professionals in working with 5G systems, regardless of their technical expertise [12]. By abstracting the complexities of the 5G network, the 5G UE AAS offers a simplified interface for managing and harnessing the capabilities of 5G technology.

In Fig. 7 we can see the 5G UE AAS enables the effective management and monitoring of a 5G UE that is part of a 5G-capable industrial device. By providing a comprehensive digital representation of the UE, the 5G UE AAS facilitates the seamless integration of 5G into production networks. Following a functional approach, akin to the 5G NW AAS, the 5G UE AAS serves as the endpoint of a 5G link and a functional component of a 5G-capable industrial device. Consequently, the 5G UE AAS should be included as a submodel of the AAS of 5G-capable devices, while the 5G NW AAS models the most relevant functions of the 5G Radio and Core networks.

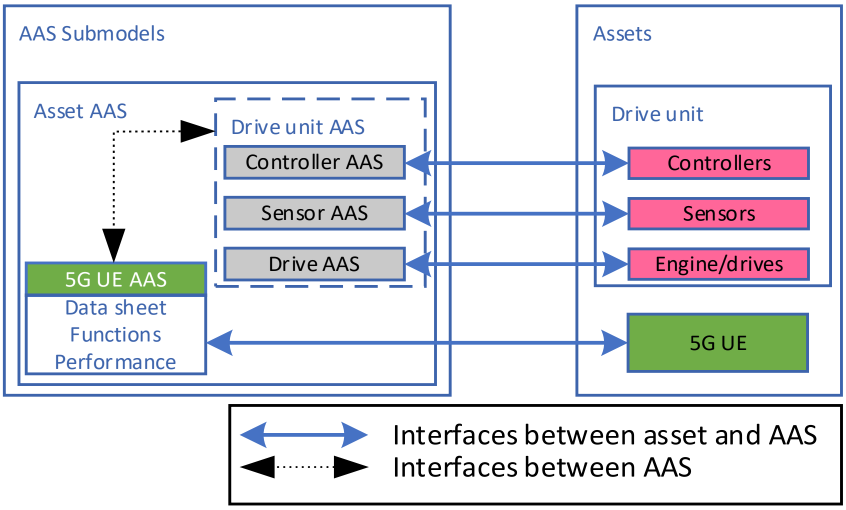


Fig. 7. Asset with 5G UE modules with their corresponding AAS

Moreover, the 5G UE AAS plays a very important role throughout the lifecycle of the 5G network, evolving and adapting to different stages to ensure its continued relevance and utility.

The 5G UE AAS consists of three main components: a passive component, an active component, and a messaging interface designed to facilitate communication in compliance with Industrie 4.0 standards. In Fig. 8 we can appreciate the passive component, properties are accessible for both reading and modification through the messaging interface, typically through an API, along with read-only properties. On the other hand, the active component houses algorithms that enable peer-to-peer communication with other AASs. These algorithms govern various aspects of interaction, including sequencing, outcome processing, and regulatory oversight, embedded within the interactive part of the 5G UE AAS.

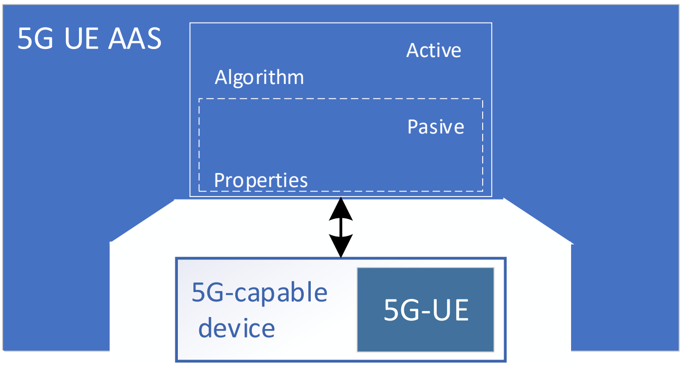


Fig. 8. Internal structure of the 5G UE AAS

The 5G UE AAS plays a crucial role in the overall functioning of the 5G network. It enables the effective management and control of user equipment, contributing to the network's efficient operation. By providing a comprehensive digital representation of the user equipment, the 5G UE AAS facilitates the seamless integration of 5G into production networks.

The Fig. 9 shows the proposed 5G AAS and the submodels that integrate it. The proposed 5G UE AAS relies on a comprehensive understanding of 5G networks, their operation and functions, and 3GPP standards. In addition, the definition of the 5G UE AAS and its submodels considers the specifications defined by Plattform Industrie 4.0 [6] about the definition and implementation of AASs, and the indications provided by 5G-ACIA. The 5G UE AAS has been implemented using the AASX Package Explorer application which is a standardized open-source tool designed for creating and managing AAS.

The Nameplate, Identification, Documentation and TechnicalData submodels have their own standardized templates in the AASX Package Explorer software. Although the Service submodel doesn't have a template, there are a few examples with similar properties in the AASX repository [10].

AAS "AAS_UE_5G" [AssetAdministrationShell---7E874932] of [https://example.com/ids/asset/4372_9062_5032_4766, Instance]
Asset AssetInformation https://example.com/ids/asset/4372_9062_5032_4766
SM "Nameplate" [https://example.com/ids/sm/8342_3111_1042_3026]
SM "Identification" [https://example.com/ids/sm/1074_5111_1042_7646]
SM "Documentation" [https://example.com/ids/sm/5542_3111_1042_4014]
SM "Service" [https://example.com/ids/sm/4572_3111_1042_7525]
SM "TechnicalData" [https://example.com/ids/sm/5372_3111_1042_7577]
SM "NetworkAccessRestrictions" [https://example.com/ids/sm/5282_3111_1042_5880]
SM "UE5GIdentification" [https://example.com/ids/sm/6092_3111_1042_0266]
SM "UEAttachAndConnectionStatus" [https://example.com/ids/sm/4382_3111_1042_2974]
SM "QosMonitoring" [https://example.com/ids/sm/8482_3111_1042_7222]
SM "Location" [https://example.com/ids/sm/0092_3111_1042_1275]
SM "UE5GDatasheet" [https://example.com/ids/sm/7423_4122_4042_5354]

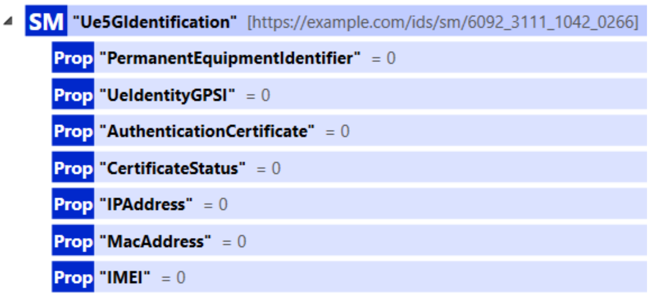
Fig. 9. 5G UE AAS and submodels.

Besides these standardized submodels, the 5G UE AAS must have its 5G-related submodels [13] since, as a vital component of the 5G network, it needs to manage 5G information. These proposed submodels have been developed based on a thorough understanding of 3GPP standards, 5G networks, their mode of operation, and functions. These submodels have been defined to include the relevant information, data and functions of a 5G UE. These submodels are: Ue5GIdentification, NetworkAccessRestrictions, UeAttachAndConnectionStatus, QosMonitoring, QosRequired, and LocalizationReport.

3.2.1 UE5GIdentification submodel

This submodel encompasses various UE identifiers as seen in Fig. 10, each serving distinct purposes within the 5G network. Among these identifiers are the IMSI (International Mobile Subscriber Identity), PEI (Permanent Equipment Identifier), and GPSI (Generic Public Subscription Identifier). The IMSI functions as a unique, non-public code assigned to each UE within a mobile network, while the PEI serves as an identifier for the terminal equipment utilized by the UE. Conversely, the GPSI acts as a public identifier, utilized both internally and externally within the 3GPP system, often associated with mobile phone numbers or MSISDNs.

Additionally, the submodel contains essential data such as the UE's PIN (Personal Identification Number), ICCID (Integrated Circuit Card ID) representing the SIM card's unique global serial number, and the Service Provider Name (SPN) identifying the serving mobile operator. Furthermore, it includes details regarding the authentication certificate, along with its status, utilized to authenticate a UE within the 5G network. Lastly, the submodel encompasses the IP and MAC addresses associated with the UE device, facilitating its network connectivity and management.



SM "Ue5GIdentification" [https://example.com/ids/sm/6092_3111_1042_0266]
Prop "PermanentEquipmentIdentifier" = 0
Prop "UeIdentityGPSI" = 0
Prop "AuthenticationCertificate" = 0
Prop "CertificateStatus" = 0
Prop "IPAddress" = 0
Prop "MacAddress" = 0
Prop "IMEI" = 0

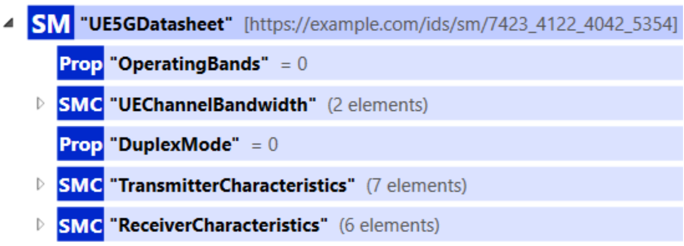
Fig. 10. Ue5GIdentification submodel

3.2.2 UE5GDatasheet submodel

This submodel comprises the technical specifications of the 5G UE, encompassing a range of critical parameters essential for its operation within the network as shown in Fig. 11. These specifications include details regarding the operating bands and duplex mode supported by the UE, providing insight into its compatibility with various network configurations.

Moreover, the submodel delineates parameters related to the communication channel, such as the maximum transmission bandwidth supported by the UE, along with specifications regarding the minimum guardband and transmission bandwidth. These parameters are crucial for ensuring efficient and reliable data transmission within the network.

Additionally, the submodel includes detailed information concerning the radio transmission and reception characteristics of the UE [14]. This encompasses key attributes such as the maximum output power, output power dynamics, and emissions of the RF spectrum. Furthermore, it outlines the reference sensitivity power level, adjacent channel selectivity, and the number of transmission and reception antennas and layers employed by the UE. These specifications are fundamental for assessing the UE's performance and compatibility with the 5G network infrastructure.



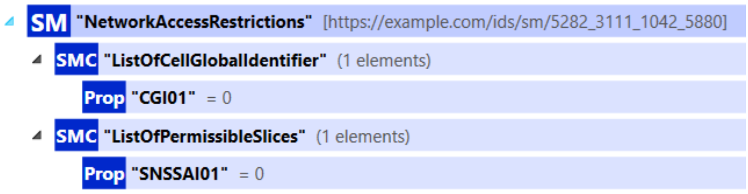
SM "UE5GDatasheet" [https://example.com/ids/sm/7423_4122_4042_5354]
Prop "OperatingBands" = 0
SMC "UEChannelBandwidth" (2 elements)
Prop "DuplexMode" = 0
SMC "TransmitterCharacteristics" (7 elements)
SMC "ReceiverCharacteristics" (6 elements)

Fig. 11. UE5GDatasheet submodel

3.2.3 NetworkAccessRestrictions submodel

This submodel encapsulates details concerning the physical and logical access constraints governing the UE's interaction with the 5G network as seen in Fig. 12. Specifically, it maintains a repository of Cell Global Identifiers (CGIs), which serve as unique identifiers for the 5G cells accessible to the UE. Additionally, the submodel houses a catalog of network slices, each identified by their respective S-NSSAIs (Service Network Slice Selection Assistance Information).

The inclusion of these lists is pivotal in delineating the permissible access points and network configurations available to the UE. Moreover, the determination of the network slices accessible to the UE is a collaborative effort between the 5G network infrastructure and the guaranteed Quality of Service (QoS) profile [15]. It is imperative that the network slices allocated to the UE possess the capability to uphold the prescribed QoS parameters, ensuring optimal performance and reliability for the UE's operations within the network.



SM "NetworkAccessRestrictions" [https://example.com/ids/sm/5282_3111_1042_5880]
SMC "ListOfCellGlobalIdentifier" (1 elements)
Prop "CGI01" = 0
SMC "ListOfPermissibleSlices" (1 elements)
Prop "SNSSAI01" = 0

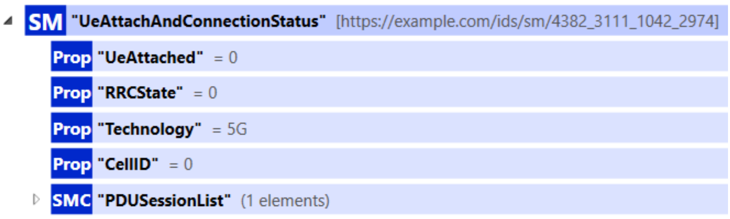
Fig. 12. NetworkAccessRestriction submodel

3.2.4 UEAttachAndConnectionStatus submodel

This submodel encompasses vital information concerning the connection status and QoS parameters of the UE within the 5G network as can be seen in Fig. 13. It includes indicators such as the UE's attachment status to the network and its Radio Resource Control (RRC) state, indicating whether the UE is active, inactive, or idle. Additionally, it maintains a list of active Packet Data Unit (PDU) sessions and QoS flows, detailing the requested and guaranteed QoS profiles provided by the 5G network.

For each PDU session and QoS flow, the submodel specifies essential Radio Resource Management (RRM) parameters necessary to maintain the guaranteed QoS profile. These parameters encompass aspects such as Modulation Coding Scheme (MCS) tables, Channel Quality Indicator (CQI) tables, target Block Error Rate (BLER), scheduling type and policy, maximum number of retransmissions for Hybrid Automatic Repeat Request (HARQ), repetition count (k), and maximum transmission power for power control.

While similar information may be available in the Connectivity submodel of the 5G NW AAS, it is essential for industrial applications implemented in 5G-capable devices to access this data directly through the 5G UE AAS. Hence, the submodel incorporates operations such as QoSRequest, enabling a UE to request specific QoS profiles from the network, and NewConnectionRequest, facilitating the establishment of new PDU sessions with requested QoS profiles. Additionally, it allows for the implementation of a ConnectionModificationRequest operation, enabling the UE to request modifications to established connections or PDU sessions, particularly concerning their guaranteed QoS profiles.



SM "UeAttachAndConnectionStatus" [https://example.com/ids/sm/4382_3111_1042_2974]
Prop "UeAttached" = 0
Prop "RRCState" = 0
Prop "Technology" = 5G
Prop "CellID" = 0
SMC "PDUSessionList" (1 elements)

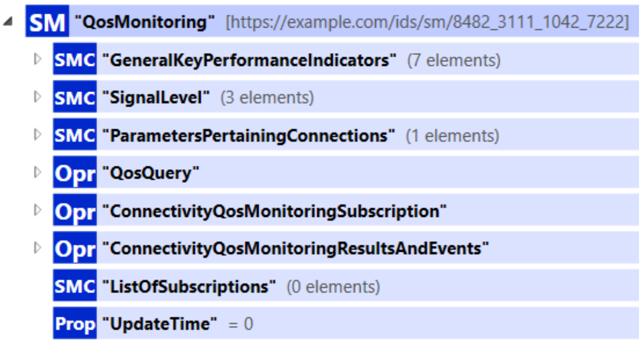
Fig. 13. UeAttachAndConnectionStatus submodel

3.2.5 QosMonitoring submodel

This submodel serves as a repository for performance-related data experienced by the UE within the 5G network as shown in Fig. 14. It encompasses various metrics reflecting the signal quality received by the UE, such as the Received Signal Strength Indicator (RSSI), Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ). Additionally, it includes performance indicators aggregated across all established PDU sessions, including average data throughput, percentage of dropped connections, handover success rate, Signal Interference Noise Ratio (SINR), average BLER, and Packet Error Rate (PER). The submodel also features an update time parameter specifying the frequency of data updates.

Aligned with the exposure capabilities of 5G, the submodel incorporates functionality for subscribing to QoS performance events from the 5G NW AAS. This enables continuous monitoring of UE QoS requirements, facilitating dynamic management and optimization of connections and network configurations. Notably, while performance data for all PDU sessions and QoS flows per UE is available through the QosPerformance submodel of the 5G NW AAS, the QosMonitoring submodel provides direct access to this information for enhanced monitoring and management capabilities.

The QosMonitoring submodel offers the SubscriptionRequestToNW operation, allowing the UE to request new subscriptions to events concerning changes in QoS performance of PDU sessions or QoS Flows. This operation can be configured to trigger notifications on-demand, periodically, or based on specific events. For example, it could be utilized to implement a monitoring function that alerts stakeholders if the experienced latency surpasses a predetermined threshold or if a minimum service bit rate is not guaranteed.



SM "QosMonitoring" [https://example.com/ids/sm/8482_3111_1042_7222]
SMC "GeneralKeyPerformanceIndicators" (7 elements)
SMC "SignalLevel" (3 elements)
SMC "ParametersPertainingConnections" (1 elements)
Opr "QosQuery"
Opr "ConnectivityQosMonitoringSubscription"
Opr "ConnectivityQosMonitoringResultsAndEvents"
SMC "ListOfSubscriptions" (0 elements)
Prop "UpdateTime" = 0

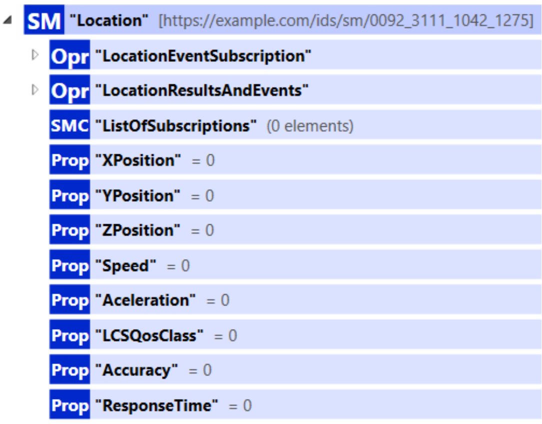
Fig. 14. QosMonitoring submodel

3.2.6 Location submodel

This submodel within the 5G UE AAS is dedicated to location-related functionalities. With the enhanced positioning accuracy offered by 5G networks, industrial applications can leverage location information for various tasks. To facilitate this integration, the Location submodel is designed to store essential information about the current location of the UE as seen in Fig. 15, including the required location service quality parameters such as accuracy and response time, indicated by the Location Services Quality Class (LCS QoS Class) [16]. Additionally, it maintains a list of subscriptions to location information provided by the 5G network and a record of notified events.

The Location submodel serves as a centralized repository for location-related data, ensuring accessibility to 5G-capable industrial devices. While the 5G NW AAS also contains location information for all connected UEs, having this data available at the UE level allows for more localized and immediate access.

One key feature of the Location submodel is the SubscriptionRequestToNW operation, enabling UEs to request new subscriptions to location events from the 5G NW AAS. For instance, UEs can subscribe to receive notifications about changes in device connections or periodic location reports. This operation enhances the UE's ability to stay informed about its location status and respond dynamically to changes in the network environment.



SM "Location" [https://example.com/ids/sm/0092_3111_1042_1275]
Opr "LocationEventSubscription"
Opr "LocationResultsAndEvents"
SMC "ListOfSubscriptions" (0 elements)
Prop "XPosition" = 0
Prop "YPosition" = 0
Prop "ZPosition" = 0
Prop "Speed" = 0
Prop "Aceleration" = 0
Prop "LCSQosClass" = 0
Prop "Accuracy" = 0
Prop "ResponseTime" = 0

Fig. 15. Location submodel

3.3 5G Network AAS proposal

The 5G system shown in Fig. 16 comprises two primary active components: the 5G UEs, as elaborated in Chapter II, and the 5G Network. Whereas a 5G UE is integrated within a device, the 5G Network is deployed throughout the entire factory across various locations. These components are categorized into two main blocks: the base station (gNB) and the Core Network (CN).

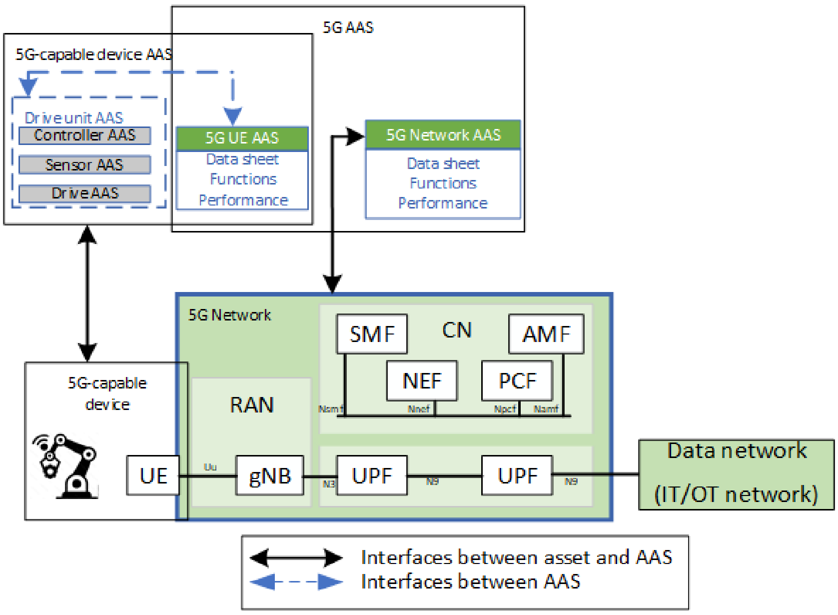


Fig. 16. 5G Network AAS architecture

The gNB (Next Generation NodeB) serves as a crucial element within the architecture of the 5G network, acting as a central hub for connecting user devices and overseeing wireless communication. With its advanced technology and capabilities, the gNB plays a pivotal role in optimizing data transmission and enhancing overall network performance. It facilitates the seamless exchange of data between UE and the network, ensuring efficient and reliable connectivity.

On the other hand, the CN (Core Network) functions as the backbone of the 5G network, responsible for managing network operations and services. This includes tasks such as user authentication, session routing, and service delivery, all of which are essential for maintaining seamless connectivity and supporting a wide range of applications. Within the CN, various nodes perform distinct functions to ensure the smooth operation of the network. For example, the UPF (User Plane Function) is responsible for managing traffic channels, while the LMF (Location Management Function) serves as a central manager for UE locations, facilitating efficient location-based services and network optimization. Together, these components work in tandem to provide robust connectivity and support the diverse requirements of modern applications in the 5G ecosystem.

As illustrated in Fig. 17, the 5G Network AAS is comprised of two distinct components. The first component, known as the passive component, functions as an information repository within the network architecture. It houses all submodels containing operational data pertinent to the network's functioning. This repository serves as a centralized source of information accessible to other users or AAS for their respective processes. A Network AAS consisting solely of the passive component would be categorized as a Type 1 AAS.

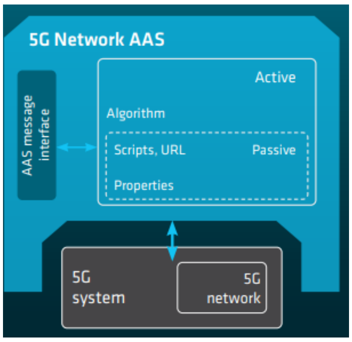
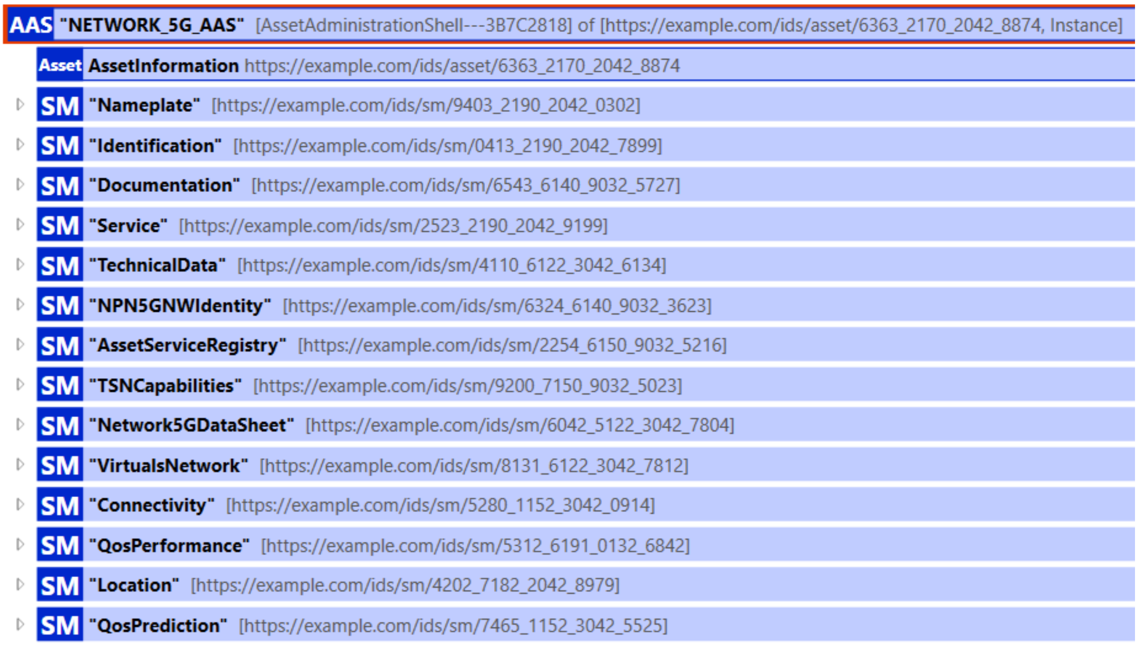


Fig. 17. 5G Network AAS [13]

In contrast, if the Network AAS is designed to interact with other AAS, it would fall into the classification of either Type 2 or Type 3 AAS. The second component, referred to as the active component, endows the Network AAS with the capability to execute behaviors such as modifying properties of a 5G UE AAS. These behaviors are typically programmed into algorithms, which are triggered by various events associated with the 5G network itself or the connected 5G UEs. The active component thus enables the Network AAS to dynamically respond to changes and events within the network environment, enhancing its adaptability and functionality.

Fig. 18 presents our proposed 5G Network AAS and its submodels, following a similar approach to the one adopted for the 5G UE AAS in Figure 3. The development of this 5G Network AAS is based on a thorough examination of 5G networks outlined in 3GPP standards, insights from 5G ACIA regarding AAS and 5G technology interaction, and guidelines from Platform Industrie 4.0 on AAS implementations. To actualize this model, we utilize the AASX Package Explorer, a standardized software for designing AAS models within the Industrie 4.0 framework.



```
AAS "NETWORK_5G_AAS"  [AssetAdministrationShell---3B7C2818] of [https://example.com/ids/asset/6363_2170_2042_8874, Instance]
    Asset AssetInformation https://example.com/ids/asset/6363_2170_2042_8874
 ▷  SM "Nameplate"  [https://example.com/ids/sm/9403_2190_2042_0302]
 ▷  SM "Identification"  [https://example.com/ids/sm/0413_2190_2042_7899]
 ▷  SM "Documentation"  [https://example.com/ids/sm/6543_6140_9032_5727]
 ▷  SM "Service"  [https://example.com/ids/sm/2523_2190_2042_9199]
 ▷  SM "TechnicalData"  [https://example.com/ids/sm/4110_6122_3042_6134]
 ▷  SM "NPN5GNWIdentity"  [https://example.com/ids/sm/6324_6140_9032_3623]
 ▷  SM "AssetServiceRegistry"  [https://example.com/ids/sm/2254_6150_9032_5216]
 ▷  SM "TSNCapabilities"  [https://example.com/ids/sm/9200_7150_9032_5023]
 ▷  SM "Network5GDataSheet"  [https://example.com/ids/sm/6042_5122_3042_7804]
 ▷  SM "VirtualsNetwork"  [https://example.com/ids/sm/8131_6122_3042_7812]
 ▷  SM "Connectivity"  [https://example.com/ids/sm/5280_1152_3042_0914]
 ▷  SM "QosPerformance"  [https://example.com/ids/sm/5312_6191_0132_6842]
 ▷  SM "Location"  [https://example.com/ids/sm/4202_7182_2042_8979]
 ▷  SM "QosPrediction"  [https://example.com/ids/sm/7465_1152_3042_5525]
```

Fig. 18. 5G Network AAS and submodels.

Given the extensive volume of data it must handle, the 5G Network AAS will surpass the 5G UE AAS in size. The network must manage communication for varying quantities of devices equipped with 5G UEs, ranging from a few to many. Each 5G UE communicates with the 5G Network to facilitate communication with other UEs, necessitating the management of traffic and location information. Consequently, the Network must process a significantly larger amount of data, encompassing not only UE information but also data related to all processes within a fully developed 5G Network.

The 5G Network is responsible for managing processes such as TSN communication to ensure precise communication between endpoints, and it must undertake the virtualization of the Network into various logical networks, with Network slices and VLANs emerging as prevalent options. To ensure seamless operations, the 5G Network requires a comprehensive 5G Network datasheet outlining general requirements and specific needs for each component of the RAN and the CN.

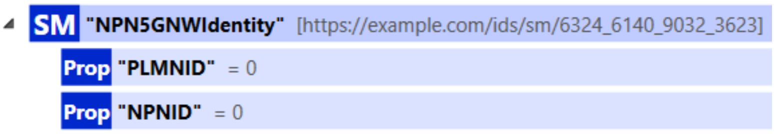
A critical responsibility of the 5G Network AAS involves managing the locations of all 5G UE AAS. This includes providing 5G UEs with their locations, assisting in locating other UEs, and managing trigger events associated with location, such as instances where two UEs are on course to collide or when a UE is out of range to receive messages.

The network's most significant and challenging task involves traffic management, overseeing traffic between every UE that sends data. This entails managing the mapping from the traffic requested by the source application to that guaranteed by the 5G Network, along with monitoring the performance of all traffic traversing the system, including trigger events involving the active part of the 5G Network.

These core tasks will be addressed by various submodels illustrated in Fig. 18. Additionally, there will be other submodels handling minor tasks or those recommended by 5G ACIA or Industrie 4.0, referred to as "Default submodels," like those implemented in the 5G UE AAS. Further details on submodel functionality and parameters will be discussed in the subsequent chapter.

3.3.1 NPN5GNWIdentity submodel

This submodel presented in Fig. 19 includes network identification information, notably the Public Land Mobile Network (PLMN) ID or Non Public Network (NPN) ID. According to 5G ACIA, these two identifiers suffice for defining a 5G Network AAS.

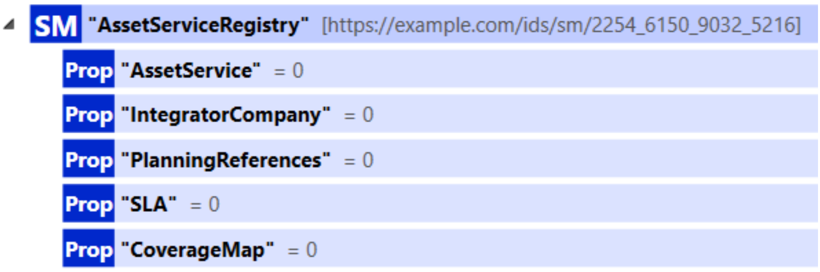


SM "NPN5GNWIdentity" [https://example.com/ids/sm/6324_6140_9032_3623]
Prop "PLMNID" = 0
Prop "NPNID" = 0

Fig. 19. NPN5GNWIdentity submodel

3.3.2 AssetServiceRegistry submodel

This submodel contains information regarding the characteristics of the 5G network during the planning and deployment phases, as outlined in [13] and seen inFig. 20. It includes the Asset Service description, the identification of the Integrator Company, and planning references. Additionally, it provides 5G coverage maps for the factory where the network is deployed, along with details about the Service Level Agreements (SLA) between the 5G network operator/provider and the factory operator. The SLA encompasses metrics for measuring the level of service and the expected performance per service type.



SM "AssetServiceRegistry" [https://example.com/ids/sm/2254_6150_9032_5216]
Prop "AssetService" = 0
Prop "IntegratorCompany" = 0
Prop "PlanningReferences" = 0
Prop "SLA" = 0
Prop "CoverageMap" = 0

Fig. 20. AssetServiceRegistry submodel

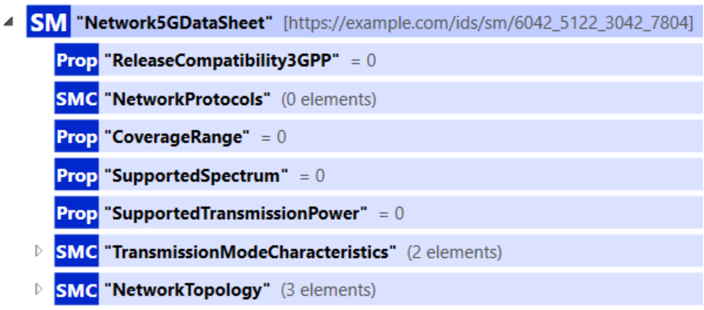
3.3.3 Network5GDataSheet submodel

This submodel encompasses information that characterizes the technical capabilities of the deployed 5G network as shown in Fig. 21. It includes details such as the supported 3GPP release, the spectrum bands utilized and supported, the maximum achievable data rates in both downlink (DL) and uplink (UL), and the supported network protocols like IPv4 and IPv6. Additionally, the submodel provides insights into the network's topology, including a comprehensive list of all Radio Access Network (RAN) and Core Network (CN) nodes comprising the deployed 5G network.

For each RAN and CN node, the submodel specifies various attributes such as:

- Node type (e.g., gNB, UPF, PCF, SMF)
- IP address
- Connections with other nodes
- Location
- Virtual machine hosting the node (if applicable)
- Computing and memory resources allocated to the virtual machine

In the case of RAN nodes, additional information is included, such as the maximum transmission power, spectrum band, receiver sensitivity, and links between nodes along with their respective capacities. This comprehensive submodel provides a detailed overview of the technical aspects and infrastructure of the deployed 5G network.



SM "Network5GDataSheet" [https://example.com/ids/sm/6042_5122_3042_7804]
Prop "ReleaseCompatibility3GPP" = 0
SMC "NetworkProtocols" (0 elements)
Prop "CoverageRange" = 0
Prop "SupportedSpectrum" = 0
Prop "SupportedTransmissionPower" = 0
SMC "TransmissionModeCharacteristics" (2 elements)
SMC "NetworkTopology" (3 elements)

Fig. 21. Network5GDataSheet submodel

3.3.4 VirtualNetworks submodel

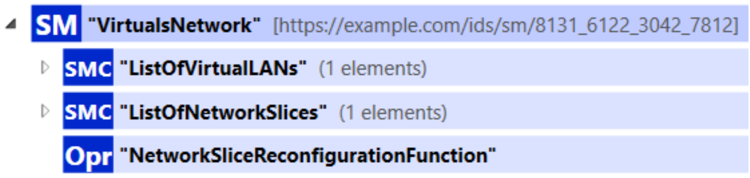
The VirtualNetworks submodel is integral to managing the implementation of virtual or logical networks in a 5G environment, allowing for the support of diverse QoS levels. One key approach to achieving this is through network slicing, a technique that leverages the virtualization and software-defined nature of 5G networks to create distinct logical networks or slices over a shared network infrastructure as presented in Fig. 22.

Within this submodel, a list of Network Slices (NS) and Virtual Local Area Networks (VLANs) is maintained. For each NS, essential details such as the Single Network Slice Selection Assistance Information (S-NSSAI) [18] and configurable attributes and values are specified. The S-NSSAI serves to uniquely identify the NS and its Slice/Service type (SST), which defines the expected behavior of the NS in terms of features and services. Standardized SSTs established by 5G include categories such as enhanced Mobile Broadband (eMBB), ultra-reliable low latency communications (URLLC), massive IoT (MIoT), V2X, and High-Performance Machine-Type Communications (HMTC) services [17].

Attributes defining a NS, as outlined by [19], encompass factors like availability, service area, isolation level, UE density, and uplink throughput per NS. The submodel also delineates the computing resources allocated to the virtual machines executing the NS.

For VLANs, the submodel specifies crucial details such as IP address, VLAN ID, priority, VLAN tag (used to identify the VLAN in a data frame), and the allocated computing resources for VLAN execution.

Moreover, the VirtualNetworks submodel features an active component responsible for implementing the NetworkSliceReconfiguration operation. This operation simulates the process of reconfiguring a network slice based on new attributes or requirements. Such reconfiguration may occur in response to dynamic adjustments needed to maintain expected performance levels, such as through a Reinforcement Learning process monitoring NS performance. If accepted by the 5G network, the operation returns the newly configured parameters of the slice.



SM "VirtualsNetwork" [https://example.com/ids/sm/8131_6122_3042_7812]
SMC "ListOfVirtualLANs" (1 elements)
SMC "ListOfNetworkSlices" (1 elements)
Opr "NetworkSliceReconfigurationFunction"

Fig. 22. VirtualNetworks submodel

3.3.5 Connectivity submodel

The Connectivity submodel within the 5G Network AAS serves as a repository of information regarding the UEs currently connected to the 5G network. It includes details such as a list of attached UEs identified by their PEI and GPSI, as well as information about established PDU sessions as seen in Fig. 23.

Each PDU session represents a logical connection between a UE and the user plane function (UPF) within the 5G system, providing access to a Data Network (DN). For each PDU session, the submodel contains a list of established QoS Flows, each identified by a unique QoS Flow ID (QFI) and characterized by a QoS profile. This profile includes various QoS parameters outlined in [18], such as the 5G QoS Identifier (5QI), Allocation and Retention Priority (ARP), Reflective QoS Attribute (RQA), Guaranteed and Maximum Flow Bit Rate (GFBR and MFBR), Notification control, and Maximum Packet Loss Rate.

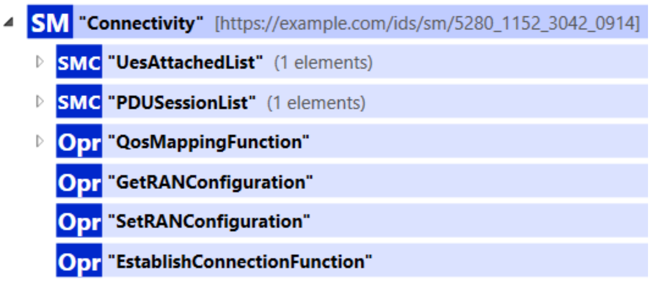
The Connectivity submodel also captures the QoS profiles requested during the PDU session establishment procedure and those guaranteed by the network after the QoS mapping process. It is noteworthy that the requested and guaranteed QoS profiles may differ if the network lacks sufficient resources, prompting potential adaptation by industrial applications to the guaranteed profile or alternative profiles [17].

In cases where network slicing is utilized, the Network Slice Reconfiguration operation can be invoked to adapt the Network Slice (NS) to support the requested QoS profile.

The submodel offers four distinct operations:

1. EstablishConnection: Emulates the establishment procedure for new PDU sessions [20] such as when a new UE is attached to the network.
2. QosMapping: Implements the QoS mapping process in 5G (defined in [20] [18]), considering the current network state to derive the guaranteed QoS profile.
3. SetRANConfiguration: Establishes values for various RAN parameters important for supporting specific QoS profiles, including modulation coding schemes, maximum retransmissions, and 5G numerology.
4. ModifyConnection: Emulates the PDU session modification procedure in 5G, enabling the modification of configuration, particularly the QoS profile, for an already established connection or PDU session.

These operations facilitate the management and optimization of connections within the 5G network, ensuring adherence to specified QoS requirements and efficient network performance.



SM "Connectivity" [https://example.com/ids/sm/5280_1152_3042_0914]
SMC "UesAttachedList" (1 elements)
SMC "PDUSessionList" (1 elements)
Opr "QosMappingFunction"
Opr "GetRANConfiguration"
Opr "SetRANConfiguration"
Opr "EstablishConnectionFunction"

Fig. 23. Connectivity submodel

3.3.6 QosPerformance submodel

The QosPerformance submodel serves as a repository of information pertaining to the performance experienced during packet transmissions, QoS Flows, or PDU sessions within the 5G network as seen in Fig. 24. This performance data encompasses various metrics outlined in [18], including service availability, reliability, PER, service bit rate, BLER, data throughput, latency, survival time, and update time.

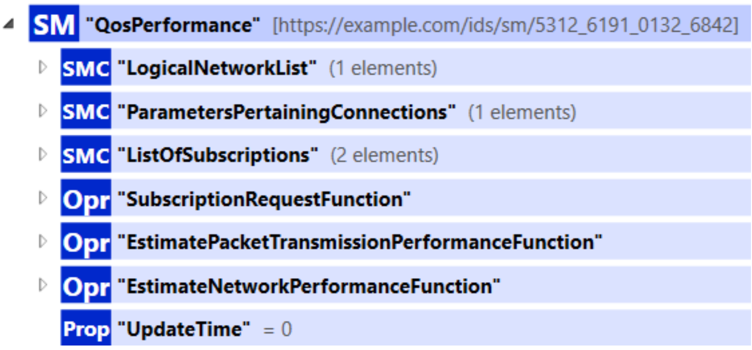
Service availability denotes the percentage of time that the service is delivered according to the guaranteed QoS profile, while reliability represents the percentage of packets successfully delivered within the latency requirement or Packet Delay Budget (PDB). PER quantifies the rate of packet errors, BLER indicates the rate of block errors, and throughput measures the data transmission rate.

Latency signifies the time taken for data to travel between its source and destination, while survival time denotes the maximum time between the reception of two consecutive packets within which the application can operate without failure. The update time parameter defines the periodicity with which performance metrics are calculated and updated.

Additionally, the QosPerformance submodel provides insights into the performance achieved within each virtual network, including network slices or VLANs. This includes metrics such as PER, BLER, reliability, latency, and throughput, computed periodically based on the configured update time parameter.

The submodel offers a list of operations to estimate performance for specific packet transmissions, QoS Flows, or PDU sessions. It also enables the provision of performance information for individual or groups of UEs over a given period. Moreover, it supports subscriptions and event notifications, allowing external applications or AAS to receive periodic, on-demand, or event-based updates regarding the QoS performance of the 5G network.

Furthermore, the submodel includes functionality for UEs or vertical applications to request new subscriptions, facilitating dynamic monitoring and management of network performance.



SM "QosPerformance" [https://example.com/ids/sm/5312_6191_0132_6842]
SMC "LogicalNetworkList" (1 elements)
SMC "ParametersPertainingConnections" (1 elements)
SMC "ListOfSubscriptions" (2 elements)
Opr "SubscriptionRequestFunction"
Opr "EstimatePacketTransmissionPerformanceFunction"
Opr "EstimateNetworkPerformanceFunction"
Prop "UpdateTime" = 0

Fig. 24. QosPerformance submodel

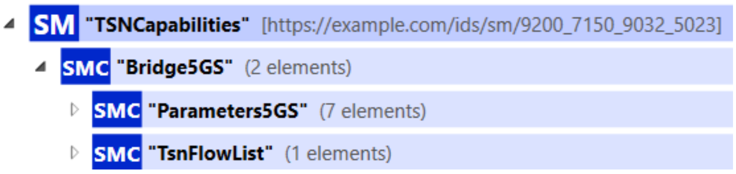
3.3.7 TSNCapabilities submodel

In integrated 5G and Time Sensitive Networking (TSN) environments, the 5G network serves as a TSN bridge, known as the 5GS Logical Bridge [17], facilitating Time Sensitive Communications (TSC). To ensure seamless integration and interoperability, the 5G Network AAS incorporates a TSNCapabilities submodel, as is customary for any TSN bridge device as presented in Fig. 25.

This submodel provides specific information tailored to the role of the 5G network as a TSN bridge. It includes essential parameters such as the 5GS Bridge delay and propagation delay per port, crucial for maintaining precise timing in TSN networks. Additionally, configuration parameters such as IP addresses, ports, VLAN-IDs, and VLAN priorities are specified to enable proper setup and operation of TSN connections.

Furthermore, the TSNCapabilities submodel enumerates the active streams corresponding to different TSN flows within the integrated network. For each TSN flow, detailed parameters from the TSC Assistance Information (TSCAI) or TSC Assistance Information are provided, including survival time, packet arrival time, and periodicity. These parameters, sourced from the TSN network, are essential for the 5G system to effectively support TSN traffic and maintain the required quality of service.

By incorporating the TSNCapabilities submodel, the 5G Network AAS ensures that the 5G network is recognized as a TSN-capable device and can seamlessly integrate into TSN environments while providing the necessary technical properties and support for TSN connections.



SM "TSNCapabilities" [https://example.com/ids/sm/9200_7150_9032_5023]
SMC "Bridge5GS" (2 elements)
SMC "Parameters5GS" (7 elements)
SMC "TsnFlowList" (1 elements)

Fig. 25. TSNCapabilities submodel

3.3.8 Location submodel

The The advent of 5G New Radio (5G NR) technology brings about a significant enhancement in positioning accuracy, paving the way for the integration of 5G positioning in various vertical applications, including Industrie 4.0. Within the 5G Network AAS, a dedicated Location submodel serves to record the precise positions of all UEs connected to the network as seen in Fig. 26.

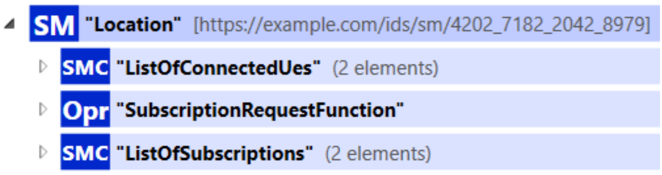
Each UE is uniquely identified using its Permanent Equipment Identifier (PEI), ensuring accurate tracking and management within the network infrastructure. The Location submodel furnishes comprehensive information, including Cartesian coordinates denoting the exact position of each UE, along with supplementary data such as speed and acceleration. This detailed positioning data is instrumental in supporting diverse industrial applications with varying requirements.

Furthermore, the Location submodel incorporates the Location Service Quality of Service Class (LCS QoS Class) [16], delineating the positioning accuracy and response time tailored to the specific needs of individual applications and UEs [20]. This ensures that the positioning services provided by the network align closely with the precise demands of each application scenario.

To facilitate seamless communication and interaction, the Location submodel includes provisions for subscriptions to various location data and events. These subscriptions can be configured to operate on-demand, periodically, or in response to specific triggering events. For instance, UEs may subscribe to receive periodic reports of their own locations, while industrial applications can subscribe to receive notifications when UEs enter or exit predefined areas of interest.

Moreover, the submodel incorporates an operation known as SubscriptionRequest, enabling UEs or vertical applications to initiate new subscriptions to location events as needed. This operation enhances flexibility and responsiveness, allowing stakeholders to dynamically adjust their location-related data requirements in real-time.

By encompassing these functionalities, the Location submodel within the 5G NW AAS ensures robust support for positioning services, catering to the diverse needs of industrial applications and facilitating seamless integration with 5G positioning technologies.



SM "Location" [https://example.com/ids/sm/4202_7182_2042_8979]
SMC "ListOfConnectedUes" (2 elements)
Opr "SubscriptionRequestFunction"
SMC "ListOfSubscriptions" (2 elements)

Fig. 26. Location submodel

3.3.9 QosPrediction submodel

With the advent of Network Data Analytics Function (NWDAF), 5G networks gain the capability not only to analyze data but also to predict the QoS of 5G connections. These predictions will play a pivotal role in enabling proactive management of the 5G network, allowing it to anticipate the connectivity requirements of the production processes it supports. This anticipation can be based on various factors such as the mobility patterns of UEs, their traffic demands, or the overall network status.

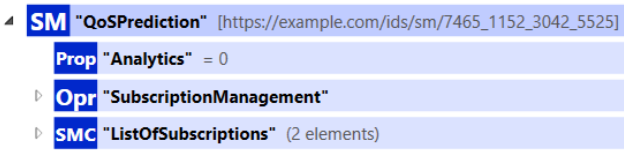
While our current implementation of the 5G Network AAS aligns with a type 2 or reactive AAS model, we have incorporated a QosPrediction submodel to facilitate its future evolution into a type 3 or proactive AAS. This submodel serves as a foundation for integrating predictive QoS capabilities into the network architecture.

The QosPrediction submodel encompasses a range of functionalities to support predictive QoS analysis. It includes a list of subscriptions that can request network QoS predictions or predictions specific to individual UE connections. For each subscription, the submodel outlines the QoS parameters to be predicted, the duration of the prediction window, and any relevant information regarding the area or path of interest where the predictions are required.

Industrial applications and stakeholders can subscribe to receive QoS prediction events tailored to their specific needs. These subscriptions can operate on-demand, periodically, or in response to predefined triggering events. Additionally, the submodel maintains a list of notified QoS prediction events, ensuring transparency and accountability in the prediction process.

To streamline the subscription process, the submodel incorporates a SubscriptionRequest as seen in Fig. 27 operation. This operation allows UEs or external applications to submit requests for QoS prediction subscriptions, specifying the desired notification frequency and mode.

By incorporating the QosPrediction submodel, our 5G Network AAS lays the groundwork for proactive network management, empowering stakeholders with predictive insights into QoS performance. This proactive approach ensures optimized network operations and enhances the overall efficiency and reliability of 5G-enabled industrial processes.



SM "QoSPrediction" [https://example.com/ids/sm/7465_1152_3042_5525]
Prop "Analytics" = 0
Opr "SubscriptionManagement"
SMC "ListOfSubscriptions" (2 elements)

Fig. 27. QoSPrediction submodel

3.4 Exploring the Role of AAS Across Diverse Use Cases

Integrating into cutting-edge technologies like 5G networks opens up a multitude of intriguing possibilities. This section delves into the dynamic landscape of 5G use cases, ranging from QoS mapping to the establishment and modification of PDU sessions, as well as the monitoring of QoS parameters and location management. Each scenario presents its unique set of challenges and opportunities, underscoring the versatility and significance of AAS in enabling seamless integration and efficient management across diverse network environments. By examining these use cases, we illuminate the pivotal role that AAS plays in shaping the future of 5G networks and beyond.

We consider an evolution of a use case proposed by 5G-ACIA in [12] that deals with QoS management in a 5G network supporting a production process. The use case is illustrated in Fig. 28 It considers a factory shopfloor where there are two 5G-capable industrial robots that have active connections with the 5G NW using their 5G UE AASs (UE1 and UE2). Each of these active connections has a guaranteed QoS profile. A new production process starts and requires high-resolution image inspection. A 5G inspection camera is activated to transmit the images to an image analysis unit on the cloud for automated inspection. The UE associated to the 5G camera (UE3) requests a new connection (or PDU session) with a high-bandwidth QoS profile (NewConnectionRequest operation in the 5G UE3 AAS). Upon reception of the new connection request, the 5G NW AAS initiates the QosMapping operation to determine the QoS profile that can be guaranteed for the new connection based on the aggregated information about the current state of the network, the QoS requested (including its priority), and the QoS profiles of the active connections. The 5G NW AAS informs the 5G UE3 AAS of the guaranteed QoS profile, and the 5G NW AAS establishes the new connection for UE3 (EstablishConnection operation). The activation of UE3 changes the network status, and the 5G NW AAS sets new RAN parameters for UE2 (using the SetRANConfiguration operation in the 5G UE AAS) to maintain its guaranteed QoS profile, e.g. it increases the number of retransmissions. In addition, the 5G NW AAS needs to change the QoS profile for the UE1 using the ModifyConnection operation in 5G NW AAS. After all changes, the 5G NW AAS estimates the performance of all three active connections to assess whether the QoS requirements are met (PerformanceOfAPDUSession operation). The QoS performance experienced is updated in the 5G UE AASs (QosPerformance submodel) and 5G NW AAS (QosMonitoring submodel), and is made accessible to industrial applications or devices through the corresponding subscriptions and events.

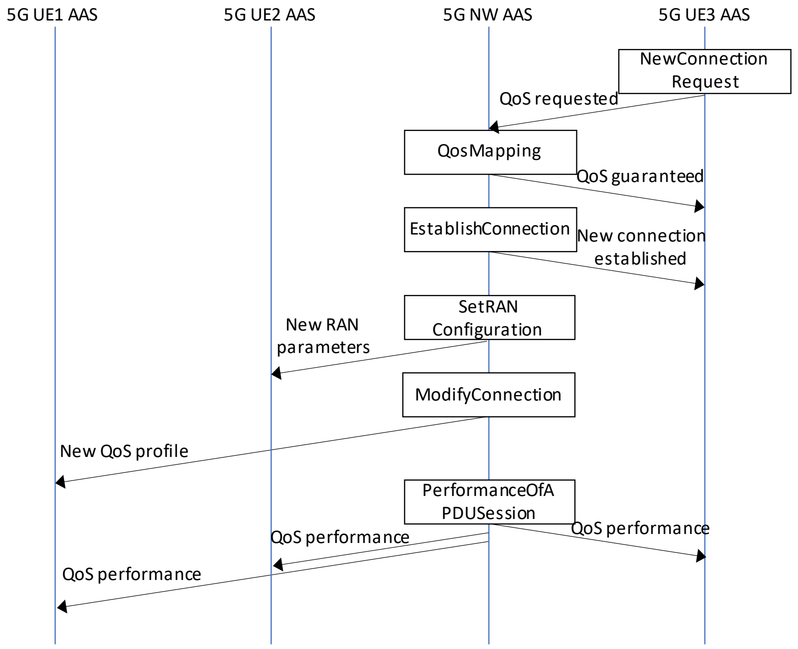


Fig. 28. 5G AAS Use Case diagram

3.5 AAS implementation

In this subsection, we transition from theoretical definitions provided by 5G ACIA and 3GPP support to practical implementation. We have realized the 5G Network AAS and the 5G UE AAS in Python, adhering to an object-oriented structure mirroring the hierarchy defined by Industrie 4.0. To accomplish this implementation, we utilized [21], which aims to translate the theory behind AAS into Python code. The Eclipse BaSyx Python project emphasizes providing a Python implementation of the AAS for Industrie 4.0 Systems, as stated in the documentation.

The Python software developed with this library furnishes us with Python classes such as AssetAdministrationShell, Asset, submodel, submodelelementcollection, and property. We can leverage these classes to create objects with attributes defined in Details Part 1 and generate as many instances as necessary. For instance, if we have three AAS, each with seven submodels, we would create three AAS objects and 21 submodel objects. Each submodel object would be associated with one AAS, and the same applies to properties.

To initiate the 5G UE AAS and the 5G Network AAS initial models, we utilized [7] to create an .aasx file. This file serves as the foundation for developing the Python AAS models available in our GitHub repository. Our designed software, built using [21], is capable of parsing .aasx files and generating corresponding AAS instances in Python. By leveraging the Basyx Python SDK, an open-source library, our software adheres to Industrie 4.0 principles, ensuring seamless integration and compatibility with AAS standards.

4. Integration of 5G AAS and Industrial plants digital models

4.1 Introduction

This chapter will include an in-depth exploration of the designed architecture aimed at integrating Asset Administration Shell (AAS) with 5G capabilities, enhancing the Industrie 4.0 components. Figure 16 illustrates the connection between Industrie 4.0 components and 5G AAS integration, facilitated by the OPC UA communication protocol. The chapter will cover the following key aspects: the Industrial Production Plant Digital Model, the 5G Digital Model module, and the OPC UA communication interface. Additionally, we will discuss the state-of-the-art of OPC UA, its role in the communication interfaces, and the functionality of the OPC UA server. Through this comprehensive examination, we aim to demonstrate the seamless incorporation of 5G capabilities into Industrie 4.0 environments, emphasizing the benefits of OPC UA in achieving efficient and flexible communication.

4.2 Integration Architecture

The architecture designed is made with the aim of integrating AAS with 5G capabilities, as well as seamlessly incorporating this 5G capabilities in the Industrie 4.0 components. As we can see in Fig. 29, the link between the Industrie 4.0 components and the 5G AAS integration will be through a communication protocol proposed by Industrie 4.0, OPC UA.

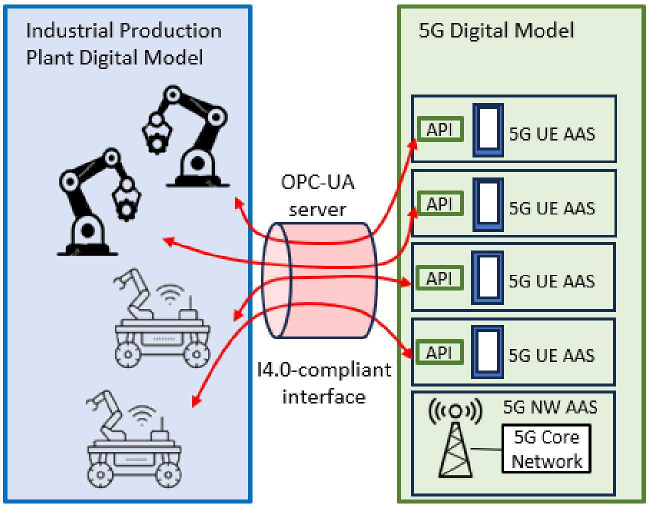


Fig. 29. Design architecture

Firstly, we have the Industrial Production Plant Digital Model module, simulated within the Visual Components software, where the industrial processes with Industrie 4.0 components are being carried out. For this paper, we have focused in two of the AGVs of the industrial production plant.We have two main tasks in this module for this AGVs: On one hand, to model two of these AGVs them and their parameters utilizing two 5G UE AASs; On the other hand, to establish communication between these two AGVs using that 5G UE AAS.

Secondly, we will introduce the 5G Digital Model module, housing the 5G AAS responsible for facilitating 5G connectivity. On one side, the 5G UE AAS will dynamically model the characteristics of the AGVs operating within the Visual Components simulation, on the other side, the 5G Network AAS will serve as an orchestrator in communication processes. Further elaboration on the models of the 5G AAS and their integration will be provided in Section III. These models will be programmed in Python using [21].

Finally, we employ OPC UA as the connection interface between the two modules. Among the various communication options advocated by the Industrie 4.0 standard for AAS, we opt for OPC UA due to its superior agility and versatility. Consequently, we have developed in Python an OPC UA communication interface tailored for AAS to facilitate seamless integration as we are going to explain in the 4.2 subsection.

4.3 OPC UA State of art

OPC UA, standardized by the IEC [22], is a platform-independent and service-oriented architecture specification critical for Industrie 4.0. The OPC Foundation has developed an extensive official standard, divided into various parts, which delineates the workings of OPC UA. It is a communication protocol specifically designed for industrial automation. It enables the exchange of information and data among devices within machines, between machines, and from machines to systems. Its primary aim is to establish a common communication standard, particularly for data exchange in automatic industrial systems, as applied in our case to AAS communication. It is secure, flexible, and scalable, allowing for the seamless addition of new clients.

We have two types of OPC UA communications, the Client/Server and the Publisher/Subscriber communication. Client/Server communication is a point-to-point communication method that has been surpassed in recent years by PubSub. It facilitates negotiations between the client and server. PubSub is an extension of Client/Server in which numerous Client/Server communications occur from a common server called the Publisher to multiple clients called Subscribers. In our case, we have been using the Client/Server OPC UA modality, where we are going to have a only client that is requesting information and responding information to the server, the Visual Components software.

OPC UA, as defined in Fig. 30, arranges information into an information model consisting of interconnected nodes [23]. Each node possesses a class and connections to other nodes, forming a hierarchically structured OPC UA address space. This address space, depicted in Fig. 30, displays the information of the OPC UA Server and is accessible by clients or real objects following [24] as a standard. The real objects that will interact with the OPC UA address space will be the Visual Components software in the Use Case that will be explained in the next chapter.

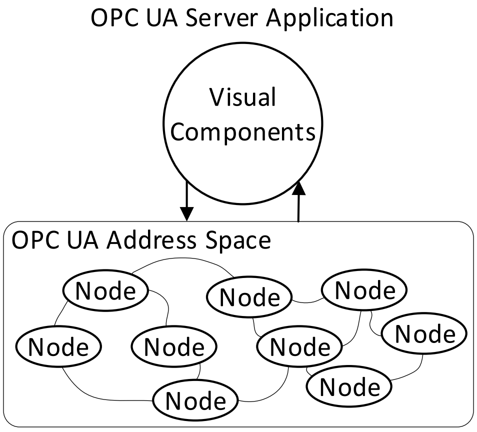


Fig. 30. OPC UA Address Space

This node-based communication method offers the advantage of enabling devices to communicate without the necessity of using identical protocols or languages. Devices simply send and receive information contained within nodes. This flexibility extends not only to diverse devices but also to different software systems that do not share the same communication protocols. As we can see in Fig. 31, every node is characterized for the attributes that define the information the own node contains and the references to the other nodes that it is connected in the structured hierarchy defined.

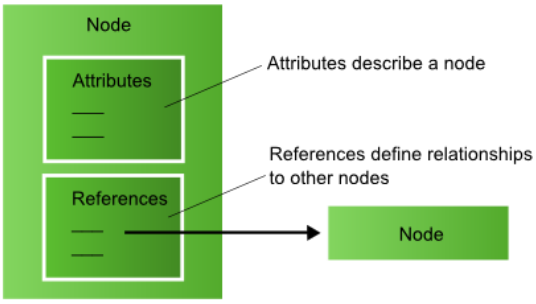


Fig. 31. OPC UA Node [25]

4.4 Communication interfaces

The OPC UA server acts as a bidirectional communication channel, facilitating data exchange between the Visual Components simulation and the various 5G AAS. Built upon [26], it utilizes the asyncua library to establish a server from an XML file, so we need to have the AAS in XML format. To map the AAS model from an .aasx file to the XML format required by the OPC UA server, we utilize again [27]. In summary, this implementation needs an. aasx model for the Python AASs and an XML model for the OPC UA server creation.

4.4.1 AAS API

The OPC UA-AAS communication interface has been designed in accordance with the guidelines outlined in [8]. This document stipulates that AAS communication should adapt to a specific set of methods: GET for reading AAS information, PUT for updating, POST for adding, and DELETE for deleting. Although these methods align with HTTP/REST principles, they are designated as the standard mode of communication for AAS, regardless of the API employed. Consequently, we have developed a communication interface that adapts these methods to OPC UA, enabling their utilization across entire AASs, an entire submodel, or just one submodel element. Although every method can interact with any element, with examples like *DELETE_AAS*, *POST_Submodel*, the most utilized methods are *GET_submodel_element* for retrieving an AAS property and *PUT_submodel_element* for updating an AAS property. In Table 1 we can see all the methods deployed.

Method	Description
GetAssetAdministrationShell	Returns the entire AAS structure
DeleteAssetAdministrationShell	Deletes an AAS
GETAsset	Returns the asset associated to the AAS
GETSubmodel	Returns an entire submodel
GETSubmodelElement	Returns a submodel element
PUTSubmodelElement	Updates a submodel element
POSTSubmodelElement	Creates a new submodel element
DELETESubmodelElement	Deletes a submodel element

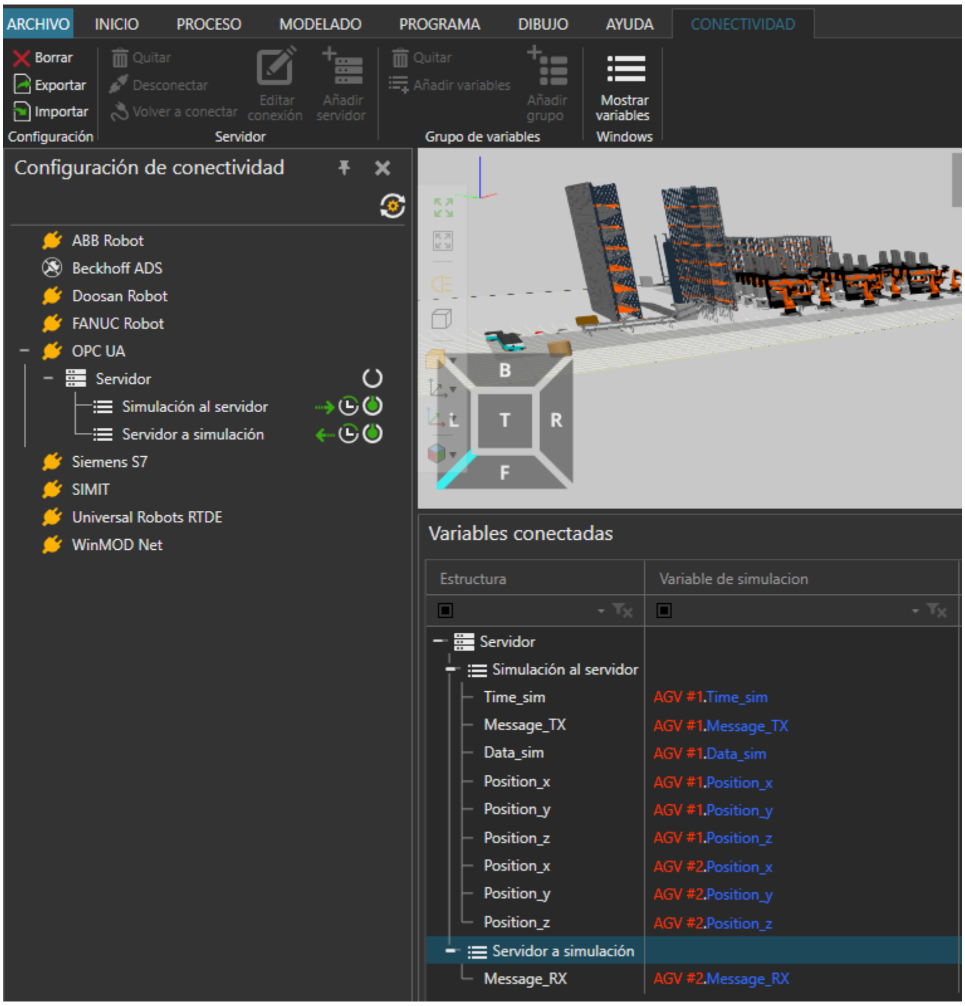
Table 1. AAS API methods

We have developed different methods to interact with the server information, although we have some complementary methods programmed in our communication interface, these ones are the examples of the methods implemented, where we can get an AAS, an asset, deleting a element of a submodel or updating it. The inputs are the AAS, the submodel or the submodel elements selected for the action.

- *GET_AAS(all_nodes,"AAS_UE_5G").*
- *GET_Asset(all_nodes,"AAS_UE_5G").*
- *DELETE_submodel_element(server, all_nodes, "AAS_UE_5G", "PDUSession02").*
- *GET_submodel_element(all_nodes,"AAS_UE_5G","Prueba_VC","Position_x").*
- *PUT_submodel_element(all_nodes,"AAS_UE_5G","UeAttachAndConnectionStatus","ARP",2,"PDUSessionList","PDUSession01","QosFlowList","QosFlow01","QosProfile","QosParameters").*

4.4.2 VC API

The VC-OPC UA communication interface allows us to establish direct associations between variables within the simulation and the OPC UA server, enabling seamless bidirectional communication. This Visual Components connectivity interface as we can see in the top of the Fig. 32, integrated within the software, facilitates the pairing of variables, ensuring efficient data exchange between the simulation environment and the OPC UA server. We can also see that VC supports other connectivity options apart from OPC UA, but they are less flexible than OPC UA and they are not as integrated with the AAS technology as OPC UA.



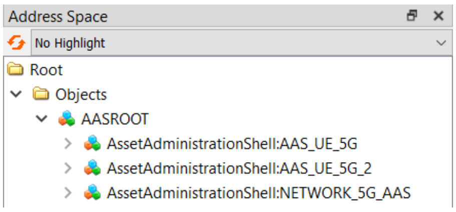
Estructura	Variable de simulacion
Servidor	
Simulación al servidor	
Time_sim	AGV #1.Time_sim
Message_TX	AGV #1.Message_TX
Data_sim	AGV #1.Data_sim
Position_x	AGV #1.Position_x
Position_y	AGV #1.Position_y
Position_z	AGV #1.Position_z
Position_x	AGV #2.Position_x
Position_y	AGV #2.Position_y
Position_z	AGV #2.Position_z
Servidor a simulación	
Message_RX	AGV #2.Message_RX

Fig. 32. Visual Components connectivity interface

Visual Components demonstrates its versatility in accommodating various communication protocols, as depicted in Fig. 32. However, OPC UA stands out by offering seamless integration with any other AAS, irrespective of its deployment location. In our scenario, with each update, we transmit a set of variables to the AAS via the OPC UA Server. Concurrently, Visual Components also receives information from the AAS through OPC UA. This bidirectional communication ensures effective data exchange between Visual Components and the AAS, facilitating synchronized operation and enhanced functionality.

4.4.3 OPC UA Server

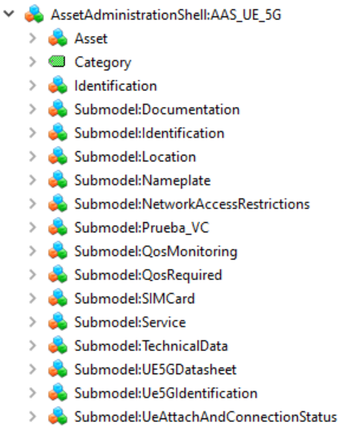
The OPC UA server will be active while the script is running following the behaviour that is programmed in python for him. Once the server is running the behavior cannot be changed, but it can be visualized through a tool that Unified Automation gives to us in [27], the UAExpert software. As we can see in the Fig. 33 the software shows us the nodes of an active server, in our case the address space of the OPC UA Server will contain the three AAS of the Use Case with the real time parameters updated with the active simulation.



Root
- Objects
  - AASROOT
    - AssetAdministrationShell:AAS_UE_5G
    - AssetAdministrationShell:AAS_UE_5G_2
    - AssetAdministrationShell:NETWORK_5G_AAS

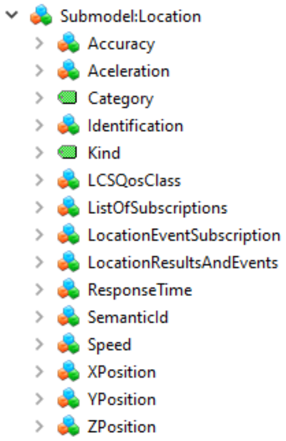
Fig. 33. AAS visualized in UaExpert

In the Fig. 34 and Fig. 35 we can see how the OPC UA nodes that represents the 5G UE AAS has exactly the same hierarchy that was shown in the Chapter 3, this “copy” of the AAS that we have on the server will allow us to communicate the AAS with any other AAS present outside of our environment or with others different softwares without the need of using the same communication protocol, for that reason OPC UA is the most valuable option for the AAS communication, because of its flexibility.



- AssetAdministrationShell:AAS_UE_5G
  - Asset
  - Category
  - Identification
  - Submodel:Documentation
  - Submodel:Identification
  - Submodel:Location
  - Submodel:Nameplate
  - Submodel:NetworkAccessRestrictions
  - Submodel:Prueba_VC
  - Submodel:QosMonitoring
  - Submodel:QosRequired
  - Submodel:SIMCard
  - Submodel:Service
  - Submodel:TechnicalData
  - Submodel:UE5GDatasheet
  - Submodel:Ue5GIdentification
  - Submodel:UeAttachAndConnectionStatus

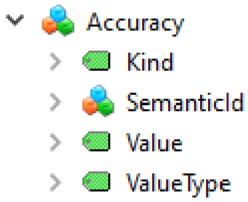
Fig. 34. 5G UE AAS UaExpert



- Submodel:Location
  - Accuracy
  - Aceleration
  - Category
  - Identification
  - Kind
  - LCSQosClass
  - ListOfSubscriptions
  - LocationEventSubscription
  - LocationResultsAndEvents
  - ResponseTime
  - SemanticId
  - Speed
  - XPosition
  - YPosition
  - ZPosition

Fig. 35. 5G UE AAS Location submodel UaExpert

In Fig. 36, we can observe the structure of a property within the 'Location' submodel. The OPC UA property structure is based on the specifications outlined in [6], which defines the attributes that a property should possess. These attributes align with those found in both [7] and [21], ensuring consistency with the standard across different technologies. The most important attribute of a property is his value.



- Accuracy
  - Kind
  - SemanticId
  - Value
  - ValueType

Fig. 36. 5G UE AAS Accuracy property UaExpert

5. Integration use case

5.1 Introduction

In this chapter, we explore a unified scenario encapsulating three pivotal use cases: connection/disconnection to/from the 5G Network Public Network (NPN), periodic location reporting, and movement events. By synthesizing these diverse scenarios into one cohesive narrative, we aim to illustrate the multifaceted capabilities of 5G AAS in industrial contexts. Our scenario delves into a dynamic manufacturing environment where seamless connectivity, real-time location tracking, and responsive event management are paramount. Through this integrated exploration, we demonstrate how 5G AAS fosters enhanced operational efficiency, proactive maintenance, and adaptive resource allocation, paving the way for a truly agile and interconnected industrial ecosystem.

Visual Components is a software platform used for 3D manufacturing simulation and visualization. It provides tools for designing, simulating, and optimizing manufacturing processes. Visual Components allows users to create virtual models of factories, production lines, and robotic systems, and simulate their operations to analyze efficiency, throughput, and potential bottlenecks. It supports the creation of layouts, robot programming, material flow analysis, and offline programming of industrial robots.

5.2 Industrial scenario

The VC scenario shown in Fig. 37 encompasses various areas, the first area on the bottom of the image is where AGVs retrieve materials from the production chain, the second area in the middle of the image where AGVs deposit materials onto robots for processing, and the third area in the top is where the final products are stored. Finally, we can see the Base Station in the top-left corner of the image. While the scenario comprises additional processes, the Use Case outlined in Section IV affects AGV movement between area 1 and area 2. Specifically, it influences the movement of AGV1 (paired with 5G UE AAS) and AGV2 (paired with 5G UE AAS 2). The scenario of the use case involves two AGVs and a Base Station within an area measuring 75.×57.86 meters. The designated pathway for AGV movement measures 70.22×4.91 meters. Additionally, six Feedline Robots marked with red rectangles situated in the bottom right corner of the figure, tasked with retrieving materials transported by the AGVs and depositing them into production lines. In this scenario we have two possible locations for the BS, the location A and the location B.

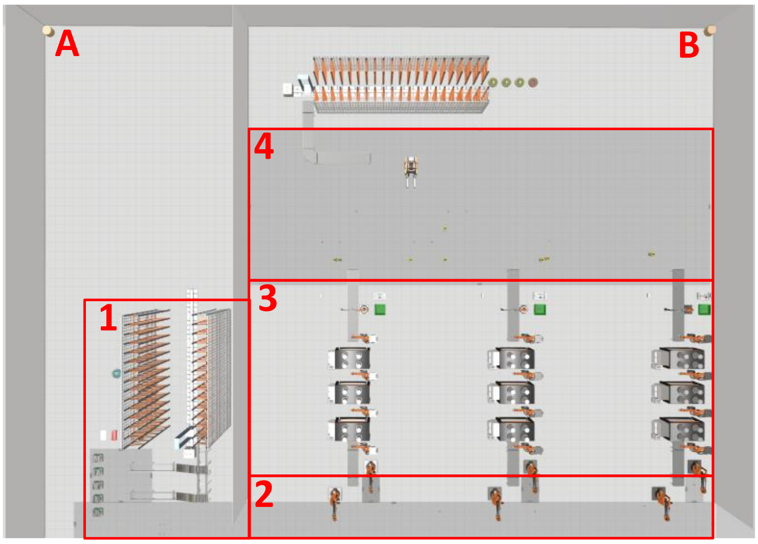


Fig. 37. Visual Components scenario

5.3 Use case description

The scenario of the use case is created within a factory floor simulated in Visual Components, where diverse industrial processes are featured. One of these processes is material transportation executed by various AGVs, serving as the focal point for the Use Case. The AGV interaction is facilitated through the architecture explained in Section IV using the 5G AAS explained in Section III. This interaction enables the periodic transmission of messages from AGV1 to AGV2 via 5G UE AAS1 and 5G UE AAS2 alongside the OPC UA interface. If more than three consecutive errors appears in the message delivery, AGV2 will stop its operations for security reasons until regular message reception resumes, which means the errors have stopped.

One of the primary goals of the use case is to facilitate communication among Industrie 4.0 components using 5G connectivity. To achieve this, a 5G communication model is integrated into the message transmission process. This model is incorporated into the 5G Network's performanceOfAPacketTx operation, which evaluates the existence of errors each time a message is sent. This operation takes the MCS and the distance between the AGV and the BS and it will obtain an error probability based on [10]. Finally, the function will determine the presence or absence of errors. Specifically, shorter distances result in a very low probability of errors, while longer distances increase the likelihood of errors. The communication process is orchestrated by the 5G NW, as depicted in the process flow diagram shown in Fig. 38.

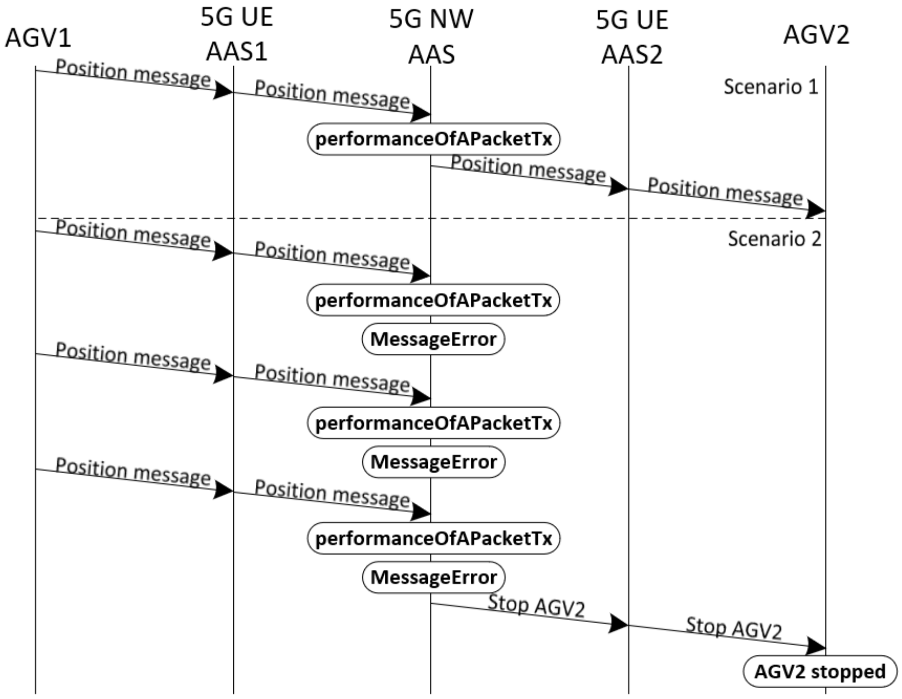


Fig. 38. **Use case flow diagram logic**

5.3.1 5G NR configuration

The 5G NW digital model models errors in a transmission using Packet Delivery Ratio (PDR) curves that relate the probability of satisfactorily delivering a packet as a function of the distance between transmitter and receiver for each modulation and coding scheme (MCS) that can be used to transmit the message. These PDR curves are derived using the model in [28] and the Look-Up Tables (LUTs) obtained through Link Level simulations using Matlab 5G toolbox [29]. The LUTs provide the Block Error Rate (BLER) as a function of the experienced Signal to Noise Ratio (SNR) and the MCS. We consider two MCSs with different error protection level: MCS10 provides high error protection with an spectral efficiency of 2.57 bps/Hz, and MCS14 that increases spectral efficiency to 3.61 bps/Hz using a lower error protection. The LUTs are derived for the Indoor Factory channel [30] and 5G NR configuration established in [31] for factory automation and presented in Table 2.

Parameter	Value	Parameter	Value
Carrier frequency	4 GHz	Channel model	Indoor Factory, TDL-C [30]
Tx power	23dBm	Conditions	Non-Line of Sight
Subcarrier Spacing (SCS)	30 kHz	Concrete wall attenuation	14 dB

Table 2. 5G NR configuration

5.4 Use case implementation

For the implementation of this scenario, several different software components are required. Initially, an aasx file containing 5G UE AAS1, 5G UE AAS2, and 5G Network AAS, each with their respective submodels, implemented in AASX Package Explorer, is necessary. Subsequently, an OPC UA Server runs with an XML file, this XML file is obtained mapping the aasx format to XML format. Additionally, this file is read in the basyx-python-sdk and stored in a structure that facilitates tasks such as finding properties, changing values, etc.

Once these initial steps are completed, a scenario is created in Visual Components. The properties of the different assets and the previously mentioned message are then linked with the server through OPC UA. The server is also connected with the AAS in basyx. The 5G Network AAS in basyx includes the " performanceOfAPacketTx " operation, which determines whether the message is transmitted correctly in the uplink and downlink.

Following these setup procedures, as described earlier, the 5G UE AAS2 communicates with AGV2 in Visual Components to either command it to stop or restart following Fig. 39 diagram, depending on the outcome of the transmission.

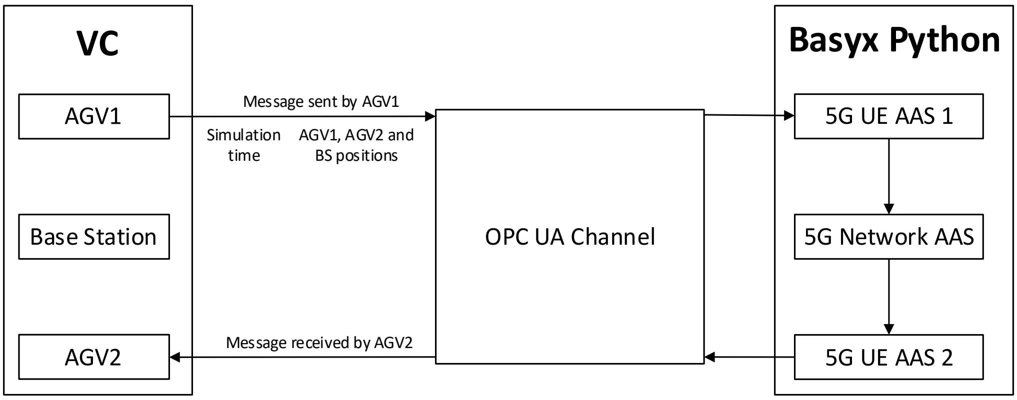


Fig. 39. Use Case diagram

AGV1 will be linked with the 5G UE AAS, while AGV2 will be paired with the 5G UE AAS 2. The communication between Visual Components and the OPC UA Server occurs through the software's Connectivity option, establishing variable pairs between Visual Components simulation variables and OPC UA Server nodes bidirectionally.

The information transmission between the OPC UA Server and the AAS deployed in Eclipse Basyx utilizes the previously defined OPC UA communication interface. Our AAS not only utilizes the OPC UA server to receive Visual Components information via deployed GET methods but also has the capability to send information using the PUT method.

We establish a periodic communication scheme wherein during each iteration, the AAS both receives and sends information to Visual Components via the OPC UA Server and its associated communication interface, as previously described. Concurrently, the AAS executes various behaviors associated with the defined use case. Incoming data triggers different events within the AAS. The AAS also generates the corresponding responses back to the simulation. This integrated approach harnesses the utility provided by the AAS to enhance the functionality of our system.

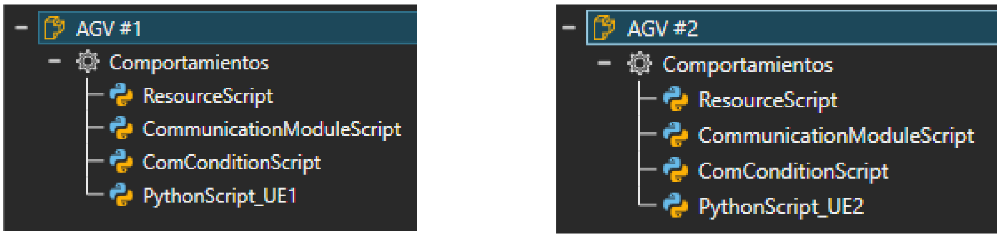
5.4.1 Visual Components Python API

The main difference between using Python in Visual Components and "normal" Python lies in the available libraries and modules specific to Visual Components. Visual Components provides its own set of modules and classes tailored for interacting with its simulation environment, manipulating components, defining behaviors, and accessing simulation data. Visual Components primarily uses Python 2.7 for scripting within its software. However, they might have updated to Python 3.x versions since then, as Python 2.7 reached its end of life in January 2020, and many software providers have transitioned to Python 3.x for compatibility and support reasons.

Python scripting in Visual Components offers a powerful and flexible toolset for simulating, analyzing, and optimizing manufacturing processes and robotic systems within a 3D environment. Key particularities include tight integration with the Visual Components API, tasks related to 3D visualization and simulation, automation of robotics and manufacturing processes, customization and extension of software functionality, data analysis and export capabilities, and the potential for plugin development to enhance the software's features. Overall, Python in Visual Components enables users to control simulation elements, create custom behaviors, analyze simulation data, and extend the software's functionality according to specific needs and requirements.

5.4.2 AGV programming

In every element of the VC scenario, we can differentiate between their properties and their behaviors, which can be seen in the Modeling interface. In the behavior section we can modelate Python (on the VC API) scripts that will serve us to modify or to add activities to the component or even to create new properties. As depicted in Fig. 40, both AGVs are equipped with different scripts. The ResourceScripts define the unique behavior of each object and are created along with the AGVs. Meanwhile, the CommunicationModuleScripts and ComConditionScripts are inherited from the scenario used but are not pertinent to this project. Finally, we have the PythonScript_UE for each UE, which are specifically tailored for this project's requirements and functionalities.



a) AGV1 scripts **b) AGV2 scripts**

Fig. 40. Visual Components AGV programming

The VC programation for this project has been divided into different sections. Firstly, we have modified the normal working of both AGVs by modifyng the ResourceScripts, introducing the property Stop that will deppend on the apperance of errors on the messages. This property is 0 by default and it will stop every action the AGV realizes in the simulation if he receive the value 1.

Secondly, we have created the PythonScript_UE1, where we programmed the logic for sending periodically a message that includes an Id and the positions from AGV1 and another message that includes a more detailed report from data of the simulation. In Table 3 we can see the start of the message sequence.

Message sent by AGV1
Id:1, PosX_AGV1:-19000.0, PosY_AGV1:-12000.0, PosZ_AGV1:1.81e-12
Id:2, PosX_AGV1:-19000.0, PosY_AGV1:-12000.0, PosZ_AGV1:1.81e-12
Id:3, PosX_AGV1:-19000.0, PosY_AGV1:-12000.0, PosZ_AGV1:1.81e-12
Id:4, PosX_AGV1:-19000.0, PosY_AGV1:-12000.0, PosZ_AGV1:1.81e-12
Id:5, PosX_AGV1:-19000.0, PosY_AGV1:-12000.0, PosZ_AGV1:1.81e-12

Table 3. Start of message sequence

Finally, we have created the PythonScript_UE2, where the message is received and processed, so we have programmed the logic that if a message is lost an error is generated, and if we count more than 3 consecutive errors in the AGV, the variable Stop mentioned before will be updated to 1, stopping the AGV. In Table 4 we can see an example of how the Id of the messges advance by 1 steps, and suddenly it get paralized in 265, that means that messages stop reaching to their destination because of the errors. When AGV2 detects that messages stop reaching it will lead to the AGV2 stop.

Message received by AGV2
Id:262, PosX_AGV1:-7834.06032009, PosY_AGV1:-18390.6173011, PosZ_AGV1:0.0
Id:263, PosX_AGV1:-6131.83747577, PosY_AGV1:-18663.7718147, PosZ_AGV1:0.0
Id:264, PosX_AGV1:-4428.62726321, PosY_AGV1:-18937.0847705, PosZ_AGV1:0.0
Id:265, PosX_AGV1:-2704.82119231, PosY_AGV1:-19107.6476175, PosZ_AGV1:0.0
Id:265, PosX_AGV1:-2704.82119231, PosY_AGV1:-19107.6476175, PosZ_AGV1:0.0
Id:265, PosX_AGV1:-2704.82119231, PosY_AGV1:-19107.6476175, PosZ_AGV1:0.0

Table 4. Message sequence with errors

5.5 Result analysis

In this subsection, we present data obtained from various simulations of the communication scenarios detailed earlier in this section. Our main simulation spans a duration of 10 hours, characterized by a PDR as described in the preceding paragraph, alongside a selected MCS value of 10. This MCS has been selected because within the range of distances from the BS that the AGVs traverse, the message error probability never exceeds 10%.

5.5.1 Communication performance

In Fig. 41 we observe the trajectory of AGV1 within a segment of the simulation of an MCS 14 with the BS in B, illustrating its movement from the material pick-up point to various robot stations. Each point on the graph signifies a specific distance traveled by AGV1 and the transmission of a message, with most messages reaching their intended destination successfully. However, a sequence of consecutive errors (indicated by red points) occurs in AGV1's transmissions. When three or more errors transpire in succession, the StopAGV2 flag is triggered (indicated by two vertical lines), stopping AGV2 until communication is restored to normality. When three or more errors occur consecutively, the StopAGV2 flags is activated till communication resumes to normality, if there are only two consecutive errors as depicted in the final of Fig. 41, nothing happens. Fig. 42 illustrates the cessation of AGV2's movement due to consecutive errors in AGV1's transmissions. This interruption is evident from AGV2's distance remaining unchanged during the stoppage period, indicating the resumption of movement only upon the receipt of messages.

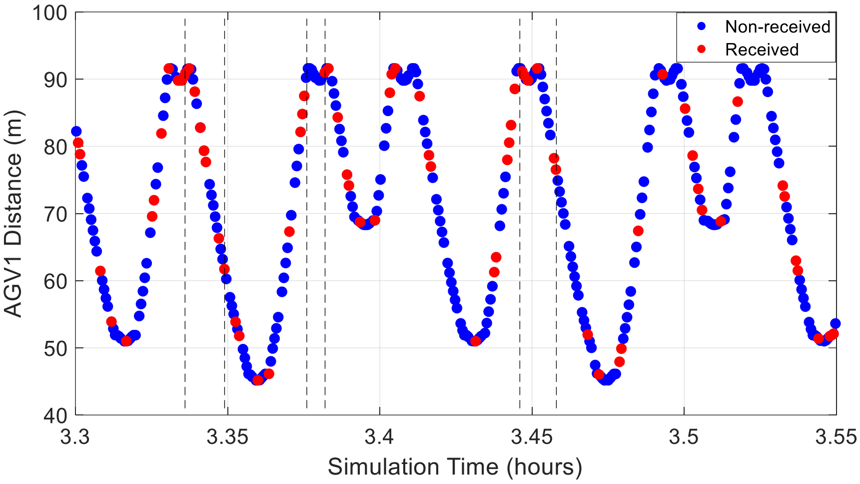


Fig. 41. AGV1 distance

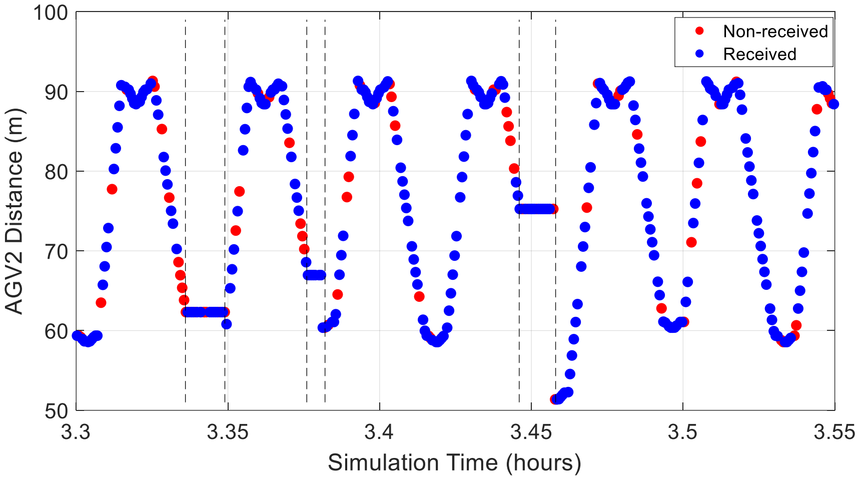
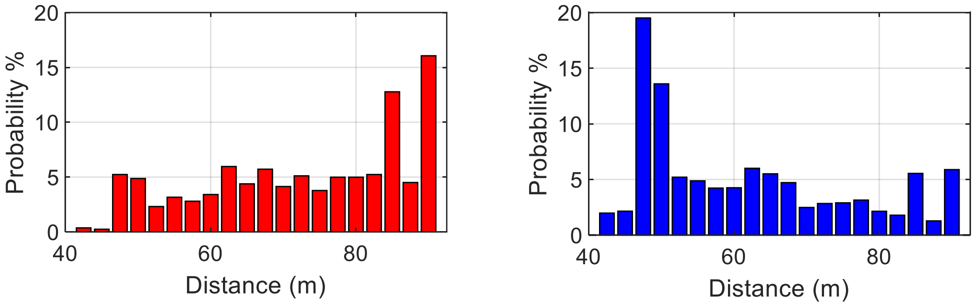


Fig. 42. AGV2 distance

Next Figures are going to illustrates the distribution of errors observed in the simulation across distance intervals of 2.5 meters. The locations of key points within the plant are delineated, with the materials pick-up points situated between 45 and 50 meters from the BS, and the robot stations positioned at varying distances thereafter: the first and second robots are located near 60 meters, the third and fourth robots around 72.5 meters, and the fifth and sixth robots between 85 and 90 meters.

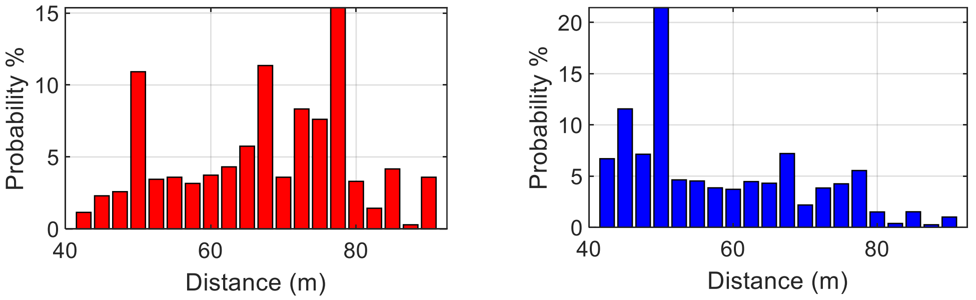
As we can see in Fig. 43.b and in Fig. 43.d histograms we can see how much time respect of the total the AGVs spent in every distance. We can appreciate the two AGVs do not spend the same amount of time in the same distances due to the scenario assigning distinct paths to each. Despite differing distributions, both AGVs spend significant time at shorter distances, where box collection from the pallet is made. However, a notable contrast emerges at the longest distances, where the scenario tends to direct AGV1 more frequently than AGV2. Consequently, AGV1 experiences higher error probabilities in these extended distances due to prolonged exposure, whereas AGV2 encounters lower error probabilities as it predominantly navigates between the first four robots.

Fig. 43.a and in Fig. 43.c histograms shows how much errors respect from the total the AGVs experiment respect from the total. This figures highlight that despite the prolonged duration spent at shorter distances, both AGVs do not exhibit high error probabilities, owing to the low error rates stipulated by the PDR. The highest error probabilities obtained from the PDR are found in the largest distances, for that reason AGV1 experimented high error probabilities in the longest distances, because he has spent more time moving around them, in contrast to the AGV2 which have been moving more between the first four robots, having very lower probability in the largest distances.



a) AGV1 error probability experimented through AGV1-BS distance

b) AGV1 percentage of time spent per AGV1-BS distance



c) AGV2 error probability experimented through AGV2-BS distance

d) AGV2 percentage of time spent per AGV1-BS distance

Fig. 43. AGVs probabilites

This communication is modeleed by a 5G PDR with a 10 MCS that affects the communication error probability. This theorical error probabilities distribution per both distances can be seen in Fig. 44, where we can see an homogeneous graph because the probabilities advance step by step as it is said in the theory, but in reality, in a 10 hours simulation we should obtain an experimented probabilities similar to that PDR as we can see in Fig. 45, although is not exactly the theorical graph, it has the same shape, corroboring the working of our simulation.

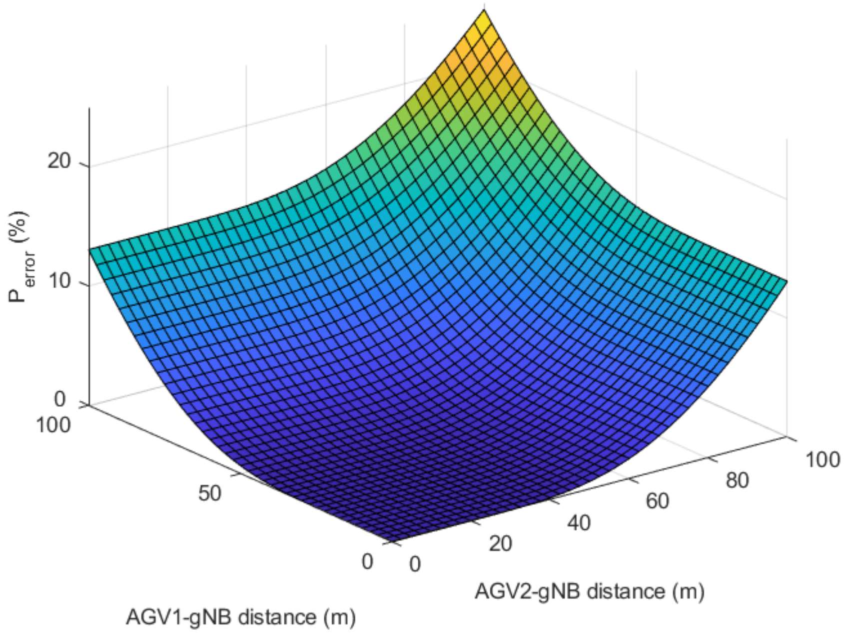


Fig. 44. Theorical error probability per distance with MCS 10

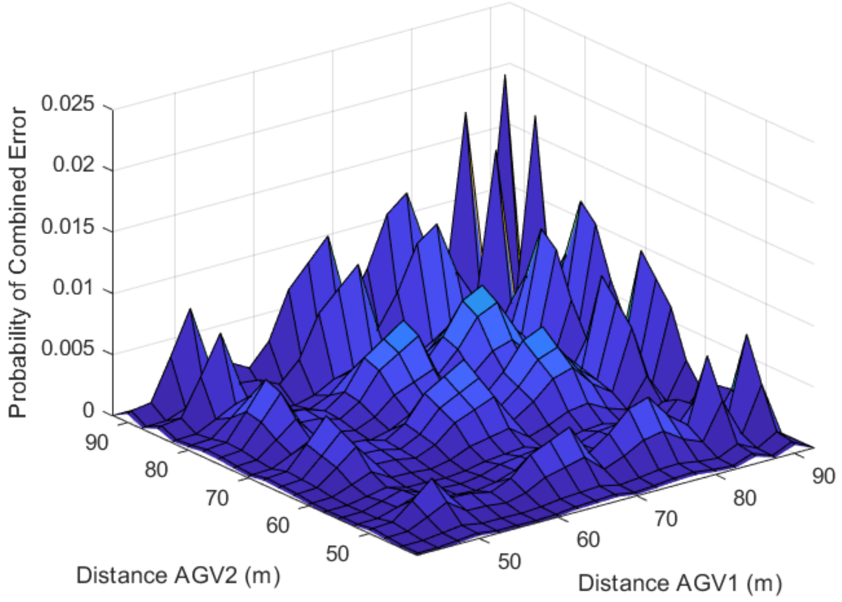


Fig. 45. Experimented error probability per distance with MCS 10

5.5.2 Impact on industrial production

Despite conducting a primary simulation with MCS 10, we also plan to conduct two secondary 10-hour simulations using MCS values of 12 and 14, respectively, resulting in higher error probabilities. This approach allows us to assess the impact of transitioning to higher MCS values, which are expected to yield more errors and consequently increase the frequency of AGV2 stops. Table 5. Error rates illustrates the escalation in transmission errors observed in both AGV1 and

AGV2. This rise in errors precipitates more frequent occurrences of three consecutive errors, thereby prolonging the duration of AGV stops.

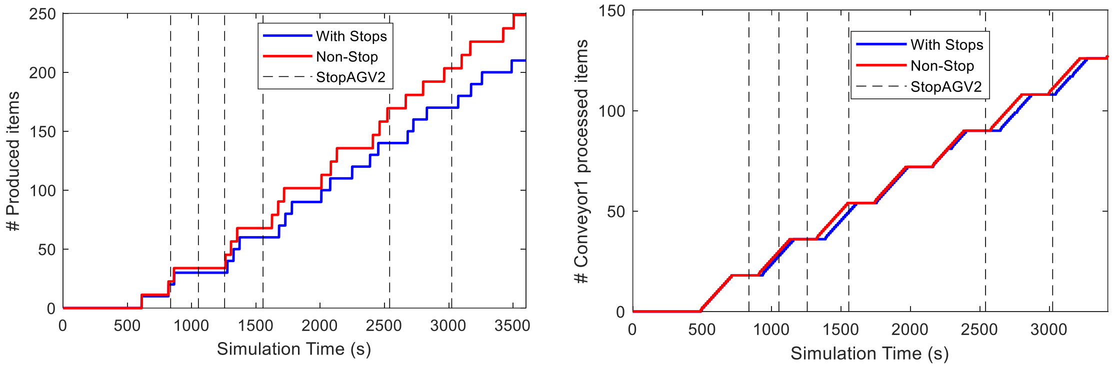
The escalation in error percentage can be appreciated with each successive increase in MCS value. However, notable variations are observed in the frequency of AGV2 stops across simulations. Specifically, there is a significant disparity in stoppage frequency between MCS 10 and MCS 12, whereas the variance diminishes between MCS 12 and MCS 14. The frequency of stops in the MCS 10 simulation is approximately eight times higher than in the MCS 12 simulation, and around 13 times higher than in the MCS 14 simulation. This discrepancy is attributed to the difficulty in encountering three consecutive errors within the MCS 10 parameters. However, as the error occurrence escalates and breaches the three-error threshold, the disparity in stoppage frequency diminishes. Consequently, the difference between stoppage frequencies in subsequent MCS iterations is less pronounced.

To evaluate the impact of AGV2 stops, we conducted several comparisons of production rates between the final conveyor (depicted at the top of Fig. 37) and the three initial conveyors (indicated by the two robots in Fig. 37). These comparisons aimed to identify any differences in production. It is important to note that each box on the final conveyor contains 10 plates, and more plates arrive on the three conveyors than are ultimately delivered, as roughly half of them are discarded during quality control checks. After running simulations, it became evident that delays in the AGV2 process, caused by its stops, significantly affect production rates. These differences are detailed in Table 5**,** where production per hour and the corresponding performance reduction percentages are clearly illustrated. We have clearly see how the BS in B locations leads to more errors.

gNB position	**MCS**	**% messages non-received**	**% of time AGV2 remains stationary**	**Avg. time between stops (min)**
A	10	4.14%	0.14%	200
	14	9.84%	2.65%	14.63
B	10	10.54%	1.24%	25.47
	14	20.62%	12.17%	5.45

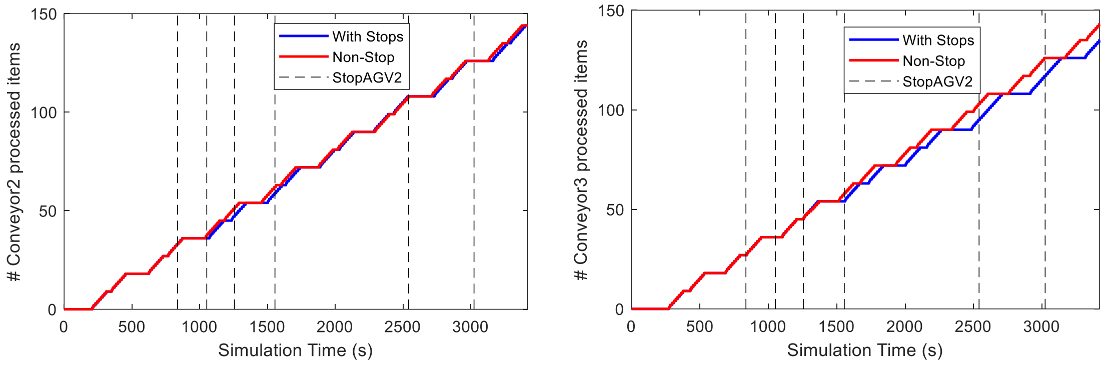
Table 5. Error rates

As evidenced i, the introduction of communication has resulted in a decrease in the production of every conveyor, with conveyor3 experiencing the most significant impact. In Fig. 46 provides a comparative visualization of the different conveyors production in simulations (with the BS in A location) with and without AGV2 stops, being the conveyor 3 the most affected by the communciation. The graph illustrates how the intermittent stopping of AGV2 has gradually delayed conveyors production and the final production shown in Fig. 46.a, corroborating the values observed in Table 5**.**



a) Final production

d) Conveyor1 production



c) Conveyor2 production

d) Conveyor3 production

Fig. 46. Conveyors production

As demostrated previously, in Table 6 we can also see how the BS in B location leads to more stops of the AGV2, so the conveyor production will be more affected where the BS is in location B. We can see how the three conveyors follows the same trend, the conveyor 3 is the most affected and the conveyor 2 is the least affected, this is because of the way the scenario and the AGV paths are built.

gNB position	Press Line 1	Press Line 2	Press Line 3	Total Production
A	2.3%	0.4%	3.8%	2.1%
B	5.5%	4.7%	7.7%	5.9%

Table 6. Production rates

5.6 Results conclusion

The results obtained from our simulations validate the theoretical framework and highlight the significant impact of 5G communication on industrial production. The primary simulation with an MCS value of 10 showed that message error probabilities remained below 10%, ensuring reliable communication within the specified range. The error rates and PDR distribution observed closely align with theoretical predictions, demonstrating the efficacy of our model.

AGV performance analysis revealed that AGV1, traversing longer distances more frequently, experienced higher error probabilities, leading to occasional stoppages of AGV2. These stoppages, triggered by consecutive communication errors, underscore the importance of robust communication channels for uninterrupted industrial processes. Higher MCS values increased error probabilities and AGV stoppages, significantly impacting production rates, particularly with the BS in location B.

Despite communication challenges, 5G connectivity facilitated real-time AGV monitoring and control, enhancing efficiency and productivity in Industrie 4.0 environments. Strategic base station placement and appropriate MCS value selection are crucial to minimize disruptions and maximize output. The integration of 5G capabilities with OPC UA for seamless communication demonstrates substantial potential for improving industrial automation, aligning with theoretical expectations, and highlighting areas for further optimization to achieve greater efficiency and reliability.

6. Conclusion and future work

6.1 Conclusion

In conclusion, this master's thesis has explored the integration of AAS within 5G networks, paving the way for transformative advancements in various industries. Through an in-depth analysis of 5G architecture, standards and protocols, this research has shed light on the dynamic landscape of 5G use cases and the pivotal role played by AAS.

The thesis has demonstrated how AAS can effectively leverage 5G networks to enable seamless communication, efficient resource management, and proactive monitoring across diverse network environments. By modeling key operations such as QoS mapping, PDU session establishment, and location management, AAS can facilitate agile decision-making and optimize network performance.

Furthermore, the integration of AAS into 5G networks unlocks new possibilities, from enhancing QoS prediction capabilities to enabling real-time monitoring of network resources and performance indicators. Leveraging tools such as SEAL servers and NEF provides essential support for executing critical operations and enhancing the functionality of AAS within the 5G ecosystem.

Through comprehensive use case scenarios, this thesis has underscored the versatility and importance of AAS in shaping the future of 5G networks and beyond. By addressing challenges such as error handling and optimizing communication processes, AAS can enhance operational efficiency, reliability, and scalability across various industries.

As we move forward, further research and innovation in the realm of AAS and 5G networks will continue to drive progress and unlock new opportunities for digital transformation. By embracing the synergies between AAS and 5G technologies, we can harness the full potential of connectivity to drive socio-economic growth and address the evolving needs of the digital era.

6.2 Future work

The integration of AAS with 5G networks presents a promising avenue for future research and development. While the current scope of this project focuses on the integration of AAS in simulated factories using only two AGVs from VC, there is ample opportunity to expand and scale up these implementations.

One area for future work involves extending the application of AAS to cover a factory in a more complete way. By deploying AAS across multiple devices and workstations within a simulated factory environment, researchers can gain deeper insights into the performance, scalability, and interoperability of the system. This expanded deployment will allow for more comprehensive testing and validation of AAS functionalities in a simulated manufacturing setting.

To achieve this vision, future research efforts should focus on several key areas. Firstly, further optimization and refinement of AAS algorithms and protocols are essential to enhance performance and adaptability in real-world scenarios. Additionally, collaborative efforts between academia, industry, and regulatory bodies will be crucial to address technical, logistical, and regulatory challenges associated with deploying AAS in industrial settings.

In summary, the future of AAS integration with 5G networks holds immense promise for revolutionizing industrial automation and manufacturing processes. By expanding deployments from simulated environments to real factories, researchers can unlock new opportunities for enhancing productivity, efficiency, and competitiveness in the manufacturing sector.

7. Bibliography

[1] Platform I4.0, *Functional View of the Asset Administration Shell in an Industrie 4.0 System Environment*, Apr. 2021.

[2] Plattform Industrie 4.0. *Language for I4.0 Components*, VDI/VDE 2193, 2020.

[3] Uwicore. 5G-AAS. Github repository: https://github.com/uwicore/5G-AAS

[4] Plattform Industrie 4.0. *Specification of the Asset Administration Shell. Part 3a: Data Specification* – IEC 61360

[5] Plattform Industrie 4.0. *Specification of the Asset Administration Shell. Part 5: Package File Format* – AASX

[6] Plattform Industrie 4.0. *Specification Details of the Asset Administration Shell. Part 1 - The exchange of information between partners in the value chain of Industrie 4.0* (Version 3.0RC02)

[7] AASX Package Explorer. Github repository: https://github.com/admin-shell-io/aasx-packageexplorer

[8] Plattform Industrie 4.0, *Details of the Asset Administration Shell, Part II*, Specification, v1.0RC02, Nov. 2021.

[9] Plattform Industrie 4.0 Swagger. DotAAS Part 2 | HTTP/REST | Asset Administration Shell Repository: https://v3-2.admin-shell-io.com/swagger/index.html

[10] Plattform Industrie 4.0. *AASX Browser based on specifications of Platform Industrie 4.0*, https://admin-shellio.com/5011

[11] Uwicore, *5G UE and Network Asset Administration Shells for the Integration of 5G and Industrie 4.0 Systems*, in IEEE ETFA 2024 - IEEE International Conference on Emerging Technologies and Factory Automation, Sep. 2024.

[12] 5G-ACIA, *Exposure of 5G Capabilities for Connected Industries and Automation Applications*, Feb. 2021.

[13] 5G-ACIA, *Using Digital Twins to Integrate 5G into Production Networks*, Feb. 2021.

[14] 3GPP, TSG RAN; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone, Rel.17, 3GPP TS 38.101, V17.8.0, Dec. 2022.

[15] 5G-ACIA, 5G QoS for Industrial Automation, Nov. 2021.

[16] 3GPP, TSG SA; 5G system (5GS) Location Services (LCS); Stage 2; Rel.17, 3GPP TS 23.273 V17.8.0, Mar. 2023.

[17] 3GPP, TSG SA; System architecture for the 5G System (5GS); Stage 2; Rel.17, 3GPP TS 23.501 V17.7.0, Dec. 2022.

[18] 3GPP, TSGS SA; Service requirements for the 5G system; Stage 1; Rel 19, 3GPP TS 22.261, V19.6.0, April. 2024.

[19] Generic Network Slice Template. GSM Association. Generic Network Slice Template Version 8.0 27 January 2023

[20] 3GPP TSG CNT; 5G System; Policy and Charging Control signalling flows and QoS parameter mapping; Stage 3; Rel.17, 3GPP TS 29.513 V17.10.0, Mar.2023.

[21] Eclipse-basyx. Basyx-python-sdk. Github repository: https://github.com/eclipse-basyx/basyx-python-sdk

[22] https://www.iec.edu.in/

[23] OPC Foundation. OPC 10000-5: UA Part 5: Information Model. Released 1.05.03. 2023-12-13.

[24] OPC Foundation. OPC 10000-1: UA Part 1: Overview and Concepts. Released 1.05.02. 2022-11- 01

[25] Unified Automation. C++ Based OPC UA Client/Server/PubSub SDK

[26] Free OPC UA. Open Source C++ and Python OPC-UA Libraries. Github repository: https://github.com/FreeOpcUa

[27] Unified Automation.UaExpert. A Full-Featured-OP-CUA-Client https://www.unifiedautomation.com/products/developmenttools/uaexpert.html

[28] M. Sepulcre, M. Gonzalez-Martín, J. Gozalvez, R. Molina-Masegosa and B. Coll-Perales, “Analytical Models of the Performance of IEEE 802.11p Vehicle to Vehicle Communications”, IEEE Transactions on Vehicular Technology, vol. 71, no. 1, pp. 713-724, Jan. 2022.

[29] Mathworks, 5G Toolbox: https://es.mathworks.com/products/5g.html

[30] 3GPP, TR; Study on channel model for frequencies from 0.5 to 100 GHz, 3GPP TR 38.901, V18.0.0, Mar. 2024

[31] 3GPP, TR; Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC), 3GPP TR 38.824, V16.0.0, Mar. 2019