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Introduction of a 5G-Enabled Architecture for the Realization of Industry 4.0 Use Cases

MICHAEL GUNDALL[1], MATHIAS STRUFE[1], HANS D. SCHOTTEN[1], (Member, IEEE), PETER ROST[2], (Senior Member, IEEE), CHRISTIAN MARKWART[2], ROLF BLUNK[3], ARNE NEUMANN[4], JAN GRIEßBACH[5], MARKUS ALEKSY[6], AND DIRK WÜBBEN[7], (Senior Member, IEEE)

[1]German Research Center for Artificial Intelligence GmbH (DFKI), 67663 Kaiserslautern, Germany
[2]Nokia Bell Labs, 81541 Munich, Germany
[3]OTARIS Interactive Services GmbH, 28359 Bremen, Germany
[4]inIT-Institute Industrial IT, Technische Hochschule Ostwestfalen-Lippe, 32657 Lemgo, Germany
[5]NXP Semiconductors Germany GmbH, 22529 Hamburg, Germany
[6]ABB Corporate Research Germany, 68526 Ladenburg, Germany
[7]Department of Communications Engineering, University of Bremen, 28359 Bremen, Germany

Corresponding author: Michael Gundall (michael.gundall@dfki.de)

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ABSTRACT The increasing demand for highly customized products, as well as flexible production lines, can be seen as trigger for the "fourth industrial revolution", referred to as "Industry 4.0". Current systems usually rely on wire-line technologies to connect sensors and actuators, but new use cases such as moving robots or drones demand a higher flexibility on communication services. Wireless technologies, especially 5th generation wireless communication systems (5G) are best suited to address these new requirements. Furthermore, this facilitates the renewal of brownfield deployments to enable a smooth migration to Industry 4.0. This paper presents results from the Tactile Internet 4.0 (TACNET 4.0) project and introduces a tailored architecture that is focused on the communication needs given by representative Industry 4.0 use cases while ensuring parallel compliance to latest developments in relevant standardization.

INDEX TERMS 5G, industrial communication, wireless communications, industry 4.0, TACNET 4.0 architecture.

I. INTRODUCTION

Digitalization has become an important topic in industrial environments. Industry 4.0 describes the "fourth industrial revolution" which enables the customization of products, the flexibility of production lines, and the efficiency of factories [1]. For this, new automation, information processing, and communication technologies are needed. A key objective is to provide a communication layer that supports the seamless access to information related to any type of product or production asset – from sensors to data-analytics services – which is stored in the so-called Industry 4.0 administration shell [2]. Administration shells are the digital representation of all data and functions of a particular product or production asset within an organization, accessible over the network in a uniform, standardized manner. They enable the discovery, negotiation, supervision and use of the production assets [3].

Beside new ("greenfield") deployments, also the renewal of existing ("brownfield") facilities require concepts to add new automation technologies. Typical applications are remote diagnostics and maintenance, logistics, process automation, and remote control, but also novel use cases are foreseen such as the usage of drones for industrial inspection, digital twins, mobile assistance systems for human-machine-interaction, or mobile robots, which require new solutions for wireless connectivity.

In order to facilitate the introduction of wireless communication systems, which meet the stringent requirements of industrial deployments, the German Federal Ministry of Education and Research (BMBF) initiated the collaborative project TACNET 4.0 [4]. The goal of TACNET 4.0 is the development of a unified industrial 5G system, which

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integrates 5G wireless technologies and industrial communication networks. 5G technologies offer the basic concepts and functions that will enable the TACNET 4.0 project to develop efficient solutions for the manufacturing industry. This includes network slicing, flexible frequency spectrum usage, edge cloud concepts, device-to-x (D2X) communication, non-public networks, and many more.

To define and formalize the requirements of industrial use cases, TACNET 4.0 has examined and classified five representative use cases [5]. Beside the use cases selected for TACNET 4.0, the most relevant approaches defined by the 3rd Generation Partnership Project (3GPP) Study on Communication for Automation in Vertical Domains [6], the International Telecommunication Union (ITU) [7], Next Generation Mobile Networks (NGNM) Alliance [8] and 5G Infrastructure Public Private Partnership (5GPPP) [9] were taken into account. Table 1 illustrates a brief summary of the representative use cases, their classification and most stringent requirements.

TABLE 1. Use cases, use case groups, and requirements overview [5].

Use case title	Use case group	Most critical requirement(s)
Cooperative Transport of Goods	Mobile Robotics	E2E latency, localization
Closed Loop Motion Control	Local and Time Critical Control	E2E latency, message error rate
Additive Sensing for Process Automation	Monitoring	Distance of entities, entity density
Remote Control for Process Automation	Remote Control	Data rate per entity
Industrial Campus	Shared Infrastructure and Intra/Inter Enterprise Communication	Guaranteed QoS, privacy

Therefore, the following contributions can be found in this paper:

- **Overview about relevant architectures and current challenges.**
- **Introduction of an tailored architecture that can face these challenges.**

Thus, the paper is structured as follows: Section II describes the potential deployment options as well as challenges and concepts for vertical communication in Industry 4.0. Section III lists the identified architecture approaches from other groups that are considered to be most relevant for TACNET 4.0 and gives a short overview on the analysis of them. Section IV specifies the system architecture in detail. Section V gives an outline of the forthcoming evaluation. Finally, Section VI concludes the paper.

II. CHANGE IN COMMUNICATION FOR INDUSTRY 4.0

Nowadays, the so-called automation pyramid dominates the design of industrial communication networks. The automation pyramid shown in Figure 1, refers to an automation system architecture where automation functions are hierarchically built on top of each other (as reflected in the ISA 95 standard [10]) and where each layer – from enterprise resource planning to the process equipment – increases in diversity (indicated by width), visually forming a pyramid. A major challenge is the heterogeneity of industrial communication protocols and interfaces that are located in the lower layers. Especially the control devices that receive sensor values and control actuators use various communication protocols, which are not necessarily compatible with each other. These so-called fieldbus protocols can differ significantly depending upon use cases, applications and manufacturers.

Ethernet-based fieldbus protocols can also be found on this level. The so-called industrial Ethernet (IE) protocols are predominantly layer 2 protocols often with modified media access control (MAC) layer [11]. This is done to meet the requirements of applications that require extremely low latency, such as motion control [12]. To address this issue, time-sensitive networking (TSN) is seen as a promising technology [13], [14]. In contrary to the field of the aforementioned operational technology (OT), the information technology (IT) area, which is found in the higher levels of the automation pyramid, uses Internet Protocol (IP)-based communication (layer 3).

A first step towards interoperability is the Open Platform Communications Unified Architecture (OPC UA) standard [15], developed by the OPC Foundation. It describes a uniform data exchange and defines both communication protocols and data models and is a main candidate for the implementation of Industry 4.0 administration shells. Since virtualization technology creates a higher abstraction level, which is an important prerequisite for both interoapability and flexibility for novel use cases, it was the subject of the investigations in [16], [17]. To realize in particular mobile use cases, there is a necessity for wireless communications. Nowadays, also wireless solutions are used in industrial environments. Typically, these applications do not use mobile radio protocols, but WLAN, Bluetooth, Wireless HART, or ZigBee. Although they cover only a small percentage of applications today, more and more use cases require wireless communication. Comparable to wire-line protocols, each of them has a different advantage regarding required transmission power, coverage, data rate, or resilience. Since emerging mobile use cases have rising demandss on wireless communication [18], they cannot be met by state of the art solutions. Here 5G is seen as a highly promising candidate. Furthermore, the convergence of IT, OT, and 5G leads to several integration challenges. To reduce the effort and cost of

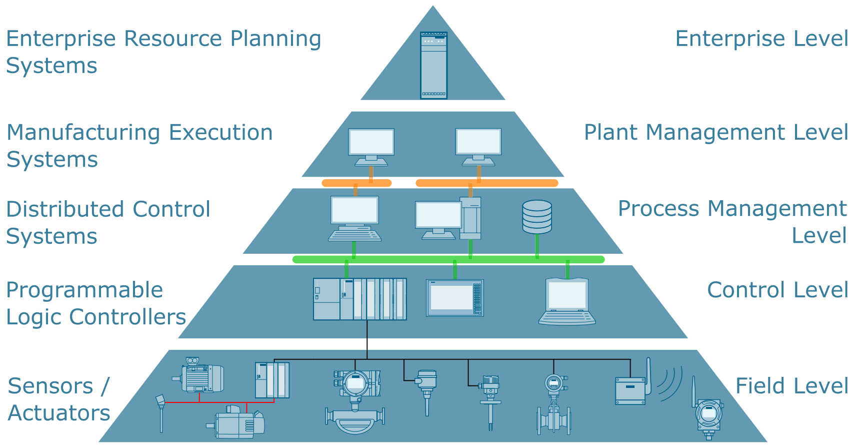

FIGURE 1. Automation pyramid.

integrating and managing a diverse set of technologies, application convergence suggests that a single network technology shall be able to meet the QoS requirements of any type of application, both for OT and IT.

A particular challenge is to connect endpoints from all levels of an enterprise for vertical integration. To provide flexibility for adaptive production, software-defined networking (SDN) is needed where resources can be reconfigured according to application needs without having to change the physical network.

To enable Industry 4.0 use cases, the above stated challenges must be faced. For this reason, the promising technologies mentioned above must be combined in a uniform architecture, whose development is a core task of the TACNET 4.0 project.

III. RELEVANT ARCHITECTURES

In this Section, the reference architectures considered are listed. In addition, the key aspects of the individual architectures are outlined.

A. INDUSTRIAL INTERNET REFERENCE ARCHITECTURE (IIRA)

Industrial Internet Reference Architecture (IIRA) [19], which is shown in Figure 2, is built on top of the Industrial IoT Analysis Framework (IIAF). IIAF provides conventions, principles and practices for consistent description of Industrial Internet of Things (IIoT) architectures. IIRA documents the result of utilizing the IIAF to the IIoT systems. IIRA defines four viewpoints (business, usage, functional, and implementation) that address stakeholder-specific requirements.

The business viewpoint focuses on the identification of relevant business stakeholders, their business vision, and values and objectives. The usage viewpoint is related to the expected system usage. The typical stakeholders here are individuals who are involved in the specification of the system. The functional viewpoint deals with the functional components of the system under development. It describes their structure, interfaces, and interactions between them as well as with external systems. The relevant stakeholders of this viewpoint are system architects, software developers, and integrators. The implementation viewpoint addresses the technologies required to realize the functional viewpoint including communications schemes and lifecycle aspects. It also provides some architectural patterns as well as patterns related to computational development. Typical stakeholders of this viewpoint are also system architects, software developers, integrators, and operators. These viewpoints are complemented by two other dimensions: system life cycle process (describing all process steps from conceptualization to disposal) and the application scope, that is addressed industrial sectors.

Moreover, the functional viewpoint is used to decompose an IIoT system into five functional domains to highlight its major building blocks, namely, control domain, operations domain, information domain, application domain, and business domain. It also describes the related functional components and the data and control flows in these domains as well as between them. The functional domains are complemented by two additional dimensions: system characteristics, such as safety, security, or reliability and crosscutting functions that are available across many of the system functional components, e.g. connectivity.

Thereby IIRA already touches most of our use case requirements, however since it is a reference architecture the guidelines are very high level. But especially the additional dimension of trustworthiness with its important system characteristics like security and privacy can be found again in the dedicated security layer of the TACNET 4.0 architecture described in the next Section.

B. REFERENCE ARCHITECTURAL MODEL INDUSTRY 4.0 (RAMI4.0)

RAMI 4.0 [20] is an Industry 4.0-related model, which is shown in Figure 3, and consists of three dimensions: hierarchy levels, life cycle & value stream, and layers. Hierarchy

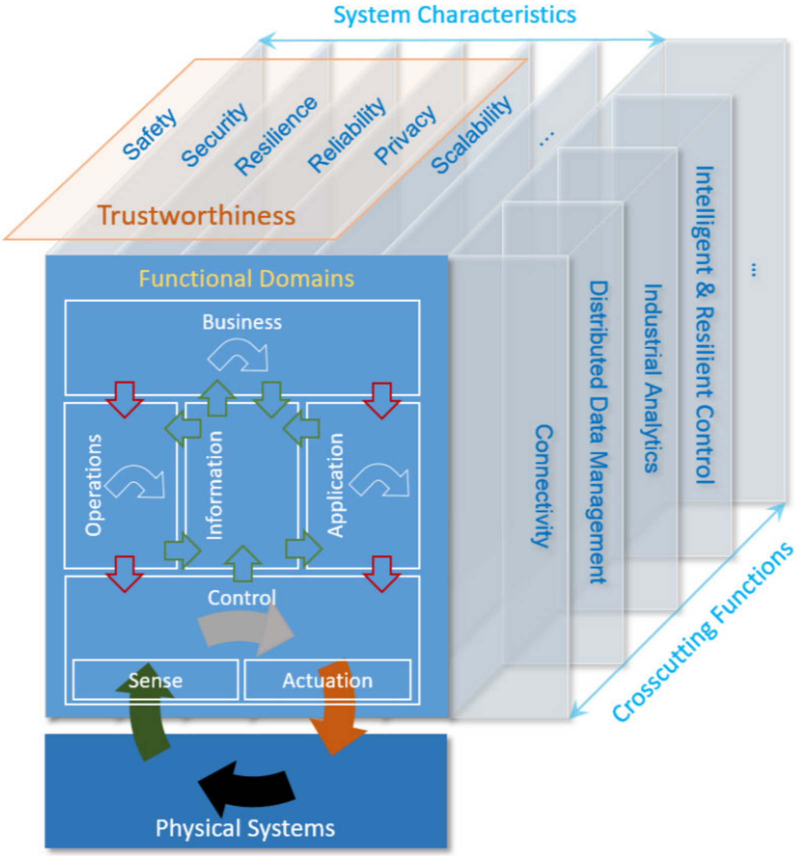

FIGURE 2. Industrial Internet Reference Architecture (IIRA) [19].

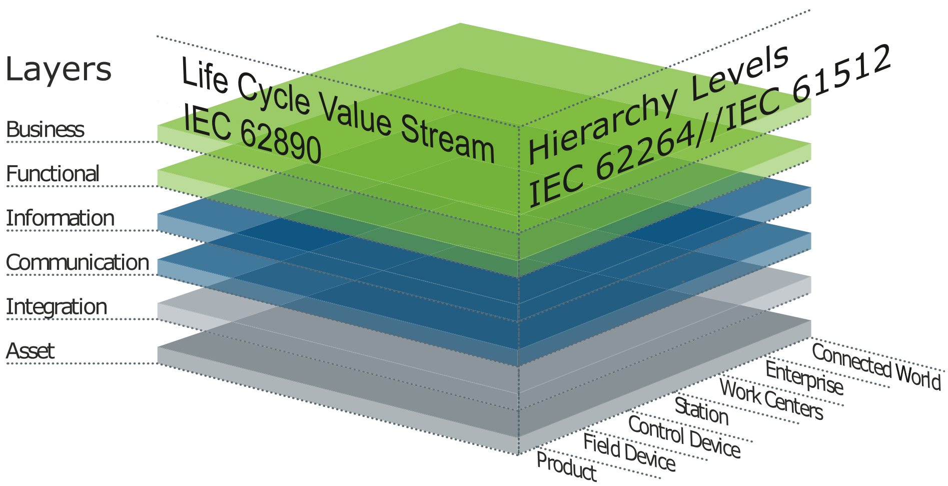

FIGURE 3. Visualization of the RAMI 4.0 [20].

levels cover the required functionalities by a factory or entire plant. They are based on the IEC 62264 [21] / IEC 61512 [22] standards and extend them by elements "product" and "connected world". Life cycle & value stream is the second dimension used in the model. It considers IEC 62890 [23] and reflects the life cycle of products and machines supporting types as well as instances. The layers describe the IT-based elements of the system in a structured way. They start with a business perspective and end on asset level.

RAMI 4.0 shares a lot of similarities with IIRA and can be mapped to each other well [24]. Especially the basic concepts and rules given within the RAMI 4.0 reference

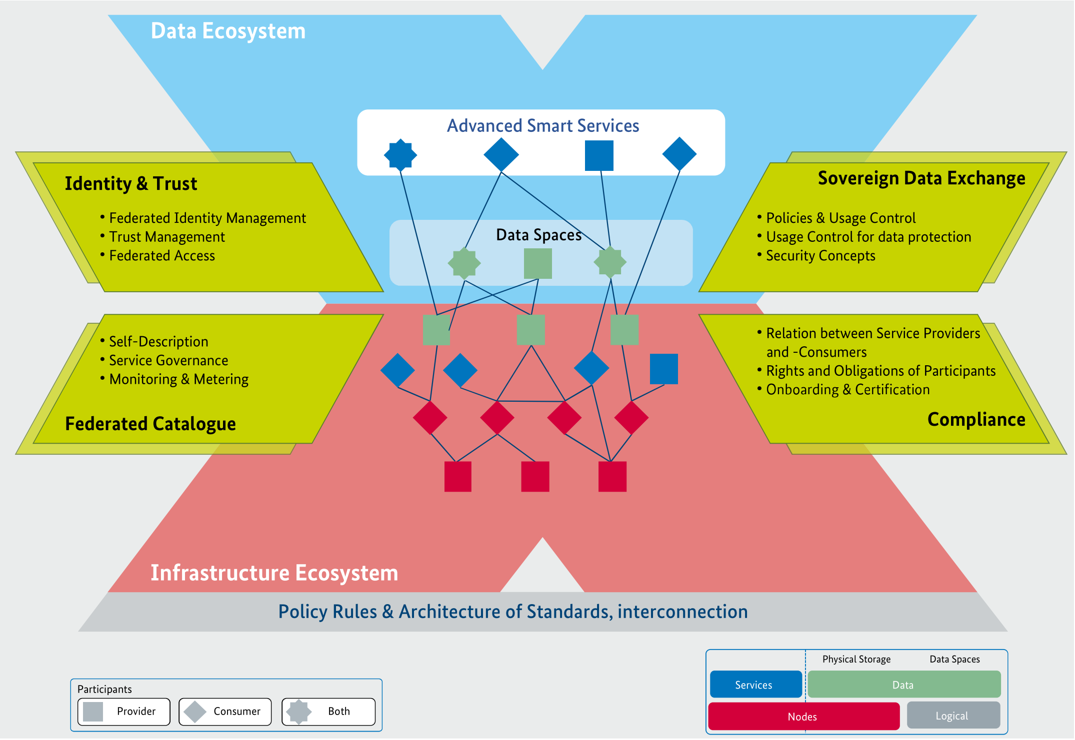

FIGURE 4. High-level overview of the GAIA-X architecture [25].

architecture e.g. about life cycle management, have been taken into account during the design of the TACNET 4.0 architecture.

C. FUNCTIONAL GAIA-X ARCHITECTURE

The GAIA-X architecture, which is shown in Figure 4, describes a cloud architecture that aims at a standardized infrastructure and data ecosystem according to European values and standards [25]. Therefore, the GAIA-X ecosystem as a whole is divided into a data and an infrastructure ecosystem. While the Infrastructure Ecosystem focuses on the provision or consumption of infrastructure services primarily through the so-called nodes, the most important asset in data ecosystems is data. Therefore, the architecture supports and enables data spaces and builds advanced intelligent services in industry verticals, where services connect both elements.

Furthermore a GAIA-X Node can represent computational resource in the range from datacenters, edge computing, basic hardware, network and infrastructure operation services like virtual machines or containers. Due to its decentralization concept, it can serve for novel industrial use cases. Thanks to the federation, small and medium-sized enterprises (SMEs) in particular, which typically cannot operate their own cloud, have the opportunity to use the cloud without having to commit themselves permanently to individual service providers. Therefore, GAIA-X can be used for services that require a data exchange with other companies, e.g. SMEs, and do not have real-time requirements.

D. FUNCTIONAL ARCHITECTURE FOR THE oneM2M SERVICES PLATFORM (ETSI oneM2M)

The oneM2M functional architecture from European Telecommunications Standards Institute (ETSI) (see Figure 5) is specified in [26] and defines a 3-layer model to support E2E machine-to-machine (M2M) services. oneM2M provides a common framework for interoperability between the many M2M and Internet of Things (IoT) technologies being introduced. Especially with the second and third release, oneM2M opens the IoT ecosystem to devices that lack the protocol and also enables the interworking among systems based on alternative approaches like AllSeen Alliance's AllJoyn, Open Connectivity Foundation's OIC, and the Open Mobile Alliance's Lightweight M2M. In particular the capability of interoperability between multiple IoT technologies within the oneM2M architecture and their management, gets introduced in the function blocks of the multi-domain manager & orchestrator (MDMO) such as registration and E2E QoS management. Even though oneM2M in Release 3 interworks with 3GPP IoT features, it doesn't reach the performance of 5G yet, which is crucial to meet the high industrial use case requirements in terms of high data rate, high entity density and low E2E latency stated in Table 1.

E. 3GPP 5G

Each 5G system (5GS) consists of the 5G core network (5GC), the 5G new radio access network (5G NR), and one or more user equipments (UEs). These components are

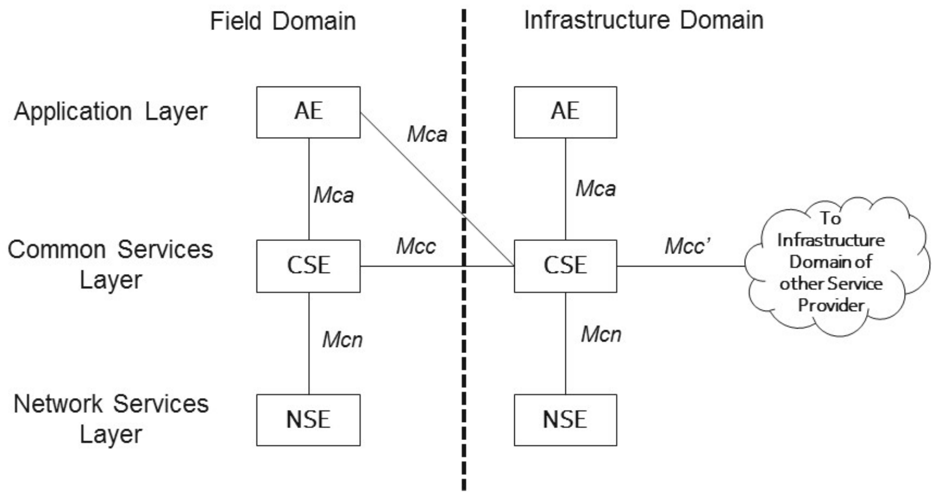

FIGURE 5. oneM2M functional architecture [26].

completed by the user, control, and management plane to enable each of the three different communication types. However, the main difference to previous mobile generations is, that the 5G architecture is service oriented. That means wherever reasonable the architecture elements are defined as network functions [27]. The generalized design of the 5G network functionalities also allow to operate with 3GPP and non-3GPP access technologies. The modular design of its network functions (NFs) and the configuration options to meet special communication requirements enables network slicing, where a slice can include control layer and E2E user layer functions. This allows individual customized and isolated logical networks.

With the Release 16 of 5G all the requirements of the use cases selected by the TACNET 4.0 project can be met. However, new findings show that not all use cases can be assigned to the categories that were introduced with Release 15, such as enhanced mobile broadband (eMBB), ultra reliable low latency communications (URLLC), or massive machine type communications (MMTC). Therefore an additional category called ''NR-Lite'' is planned for Release 17, which will be available until the end of 2022 [28]. To address this issue, non-3GPP access technologies are also taken into account. In addition, not yet considered are the interconnection with brownfield technologies such as Industrial Ethernet or the upcoming TSN which will be essential to fulfill real-time use cases. To guarantee real-time within 5G, a TSN translator was developed within the project. Since the 5G architecture serve as the main basis for the TACNET 4.0 architecture, the division into the application managemement and orchestration (MANO), control, and data layer can also be found in the TACNET 4.0 architecture described in the next Section. The data layer is the part of the network which is used to transfer the data traffic of the user. Packet routing is performed at this level. The control layer is responsible for establishing, monitoring, and terminating connections. The management & orchestration layer coordinates the 3GPP core network (CN), the network functions virtualizations (NFVs), and resources for the control and data layer. The service layer comprises of all communication and industrial applications as well as required services like synchronization or localization retrievable by the control and data layer. Since the focus in 3GPP 5G is on industrial applications the proposed TACNET 4.0 architecture gets extended by an application layer as well as a security layer to unify all domain specific security functions.

F. 5GPPP 5G NOVEL RADIO MULTISERVICE ADAPTIVE NETWORK ARCHITECTURE (5G NORMA)

The 5GPPP functional 5G Novel Radio Multiservice Adaptive Network Architecture (5G NORMA) architecture (see Figure 6) is designed to dynamically adapt the use of the mobile network infrastructure to the service requirements, the variations of the traffic demands over time and location, and the network topology [29] and incorporates four layers. On top is the service layer which comprises of business support systems, business-level policy and decision functions as well as applications and services operated by the tenant. The MANO layer extends the ETSI NFV MANO towards multi-tenant and multi-service networks. To achieve this, this layer also includes the virtualized infrastructure manager (VIM), virtualized network function (VNF) manager, network functions virtualization orchestrator (NFVO) as well as any application management function from various domains, e.g. the 3GPP domain. The control layer comprises the software-defined mobile network coordinator (SDM-X) for the control of shared NFs and the software-defined mobile network controller (SDM-C) for dedicated NFs. At the bottom, the data layer includes the VNFs and physical network functions (PNFs) required to transport and process the user data traffic.

The extension of the 5G architecture by the network slicing concepts developed in 5G NORMA and SDN give on

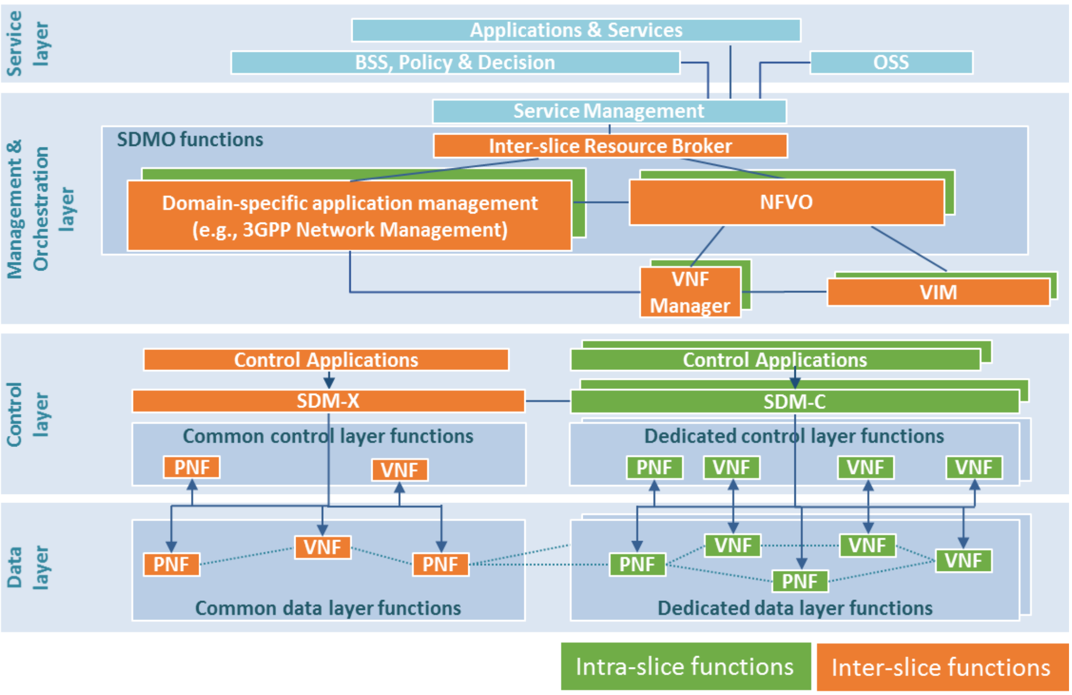

FIGURE 6. Functional perspective of the overall 5G NORMA Architecture [29].

one hand more freedom in the use of network management mechanism and also more control by providing guaranteed QoS which is also one important requirement to fulfill the varying demands of the use cases and therefore the network slicing management is also integrated in the TACNET 4.0 architecture.

G. SUMMARY

Looking deeper into the different architecture approaches, the question arises, which one is best suited for TACNET 4.0. While the presented architectures share some similarities, there are also differences where each approach focuses on. For example, the 3GPP architecture scope is set on wireless communication using 5G technologies, oneM2M on interoperability between multiple IoT technologies, RAMI 4.0 on the manufacturing of products covering the complete life cycle, IIRA on the general design of industrial internet systems, GAIA-X on enablement cloud technology with common specifications and standards, and finally 5G NORMA is set on the logical separation of a physical network structure. Based on these aspects and the fact that none of the approaches is focused on the integration of 5G and Industry 4.0, it is evident that the design of a tailored architecture for TACNET 4.0, which has the claim to be compliant to the existing approaches, is a suitable strategy.

IV. OVERALL SYSTEM ARCHITECTURE

This Section is dedicated to the functional architecture developed in TACNET 4.0. First, the design process is explained (see Section IV-A). Subsequently, Section IV-B describes the most important technology concepts, which serve as the fundament for the TACNET 4.0 architecture. Since a detailed description of all developed functions is not feasible, selected components are explained in Section IV-C.

A. ARCHITECTURE DESIGN PROCESS

The architecture development process, which is explained in detail in [30], comprises of four design phases that are shown in Figure 7 and are summarized below.

The first step is to define the targeted applications and their requirements that the architecture needs to handle (top-down approach). Therefore, a use case and requirements analysis was carried out [5]. The second phase comprises of the definition of functional components including required in- and output metrics to realize the use cases. With the help of the message sequence charts, the interactions between single functions are described and missing interfaces are identified. After an iterative process of phase 2 and 3, the result the complete functional architecture, which is depicted in Figure 8. Since the layers that we use in our approach have already been introduced, the following Section directly starts describing the base components that can be found in the TACNET 4.0 architecture.

B. BASE COMPONENTS OF THE TACNET 4.0 ARCHITECTURE

1) DATA TERMINAL EQUIPMENT (DTE)

A DTE is an industrial device, such as sensor or actuator, that should be connected wirelessly. In addition, it provides an

FIGURE 7. Architecture development process [30].

industrial interface that has to be used for the data exchange with the DCE.

2) DATA COMMUNICATION EQUIPMENT (DCE)

To transmit data using an industrial protocol, the DCE provides the signal conversion, coding of the data to and from the DTE. In the 3GPP domain this would be the UE which is wirelessly connected to the RAN.

3) RADIO ACCESS NETWORK (RAN)

The RAN provides and manages all resources to connect wireless devices via the air interface to the backbone or CN. It includes all 3GPP technologies like EUTRAN and 5GNR as well as non-3GPP, e.g. Wi-Fi or Industrial Radio.

4) CORE NETWORK (CN)

The CN offers all functions to control authentication of subscribers, manage the mobility of connected devices and route user traffic. While the 4th generation wireless communication systems (4G) CNs were based on functions the 5G CN is service-based. A full list of services can be found in [27].

5) SOFTWARE-DEFINED NETWORKING (SDN)

In order to benefit from the flexible resource deployment in adaptive production SDN plays an important role. The physical separation of the network control plane from the forwarding plane is the main concept behind SDN. That allows much more dynamic, manageable and cost-efficient networks compared to traditional networks. To achieve this, there are two fundamental SDN elements defined:

- SDN switch: a SDN switch receives and forwards data packets, following the rules in the flow tables that are managed by the SDN controller via SDN protocols like OpenFlow [31].
- SDN controller: a SDN controller is the centralized management unit of the network that allows for dynamically managing the flow-tables. Two common used SDN controllers, which are also used in TACNET 4.0, are OpenDaylight [32] and ONOS [33].

6) INDUSTRIAL ETHERNET (IE)

For a smooth transition to a wireless industrial environment it is important to support brownfield technologies such as IE. IE applies Ethernet-based data communication to manufacturing control and production networks. It includes all levels from sensor/actuator connectivity and real-time control.

7) TIME-SENSITIVE NETWORKING (TSN)

For covering not only brownfield technologies, also upcoming communication standards, such as TSN, are required to realize all machine control use cases. TSN is an Ethernet extension (IEEE802.1Q) [13] designed to make Ethernet-based networks deterministic. To achieve this, there are four main components specified:

- TSN end station: a TSN end station is either the source or destination of the time-critical communication.
- TSN bridge: a TSN bridge is basically an Ethernet switch that is capable of transmitting, scheduling and receiving TSN Ethernet frames.
- TSN centralized network configuration (CNC): the CNC schedules the TSN frames for the requested communication in all TSN Bridges.
- TSN centralized user configuration (CUC): the TSN CUC is connected to the TSN CNC and TSN end stations and configures the TSN end stations according to the specific time-sensitive requirements.

8) 3GPP MANAGEMEMENT AND ORCHESTRATION (MANO)

The 3GPP MANO is responsible for performance, fault and alarm management in both RAN and CN within the 3GPP system.

9) NETWORK FUNCTIONS VIRTUALIZATION MANO (NFV MANO)

Towards the convergence of IT and OT networks by Industry 4.0 virtual IT resources become more and more important. Similar to the 3GPP domain, the NFV MANO is an architectural framework defined by ETSI to facilitate the life cycle and connection of all virtualized services. It consists mainly of five functional blocks.

- Network functions virtualization orchestrator (NFVO): the NFVO has access to the VNF catalog and orchestrate the needed compute and network resources. Therefore it computational liaises closely with the VIM.
- Virtualized network function (VNF) manager: the VNF manger instantiates, scales, updates and terminates VNFs.
- Virtual infrastructure manager (VIM): the VIM is mainly responsible for the allocation of the virtual resources to the physical resources.
- Container orchestration: similar to the NFVO, there is also the container orchestration located in the MANO. The tasks of this entity are the automated provisioning and deployment of containers.

- Container infrastructure manager: its tasks are the coordination of physical hardware resources (compute, storage, networking) and their provision for an automated container deployment.

C. SELECTED COMPONENTS OF THE TACNET 4.0 FUNCTIONAL ARCHITECTURE

This section describes the most relevant extensions to the existing technologies, developed by the TACNET 4.0 project.

1) RADIO TECHNOLOGY MANAGEMENT (RTM), SPECTRUM MONITORING (SM) & SPECTRUM MANAGEMENT (SMM)

For the allocation of existing radio resources and the selection of an appropriate radio access technology (RAT), the RTM in conjunction with SM and SMM plays a central role [34]. The SM is responsible for the monitoring and the SMM for allocation and release of physical resources.

For applications in the industrial environment, spectrum allocation can take place for a longer dedicated period of time. In order to enable a suitable allocation of the spectrum, the SMM unit is equipped with databases containing all necessary information. However, this is only valid as long as there is no interference in this area, which can be caused e.g. by jamming or inter-cell interference. Therefore, TACNET 4.0 monitors the spectrum in order to detect these interferences and initiate a suitable reallocation, such as a channel change. If necessary, a change to another RAT can also be arranged in cooperation with the RTM. To enable a suitable SMM, the TACNET 4.0 architecture provides an interface to interconnected SM units, which belong to the RAN logically (see Figure 8).

Particularly in an industrial context, high time requirements arise, as shown in Section 1. Accordingly, the system must be able to react quickly to changes and make adjustments. Each request will be triggered by the network resource management (NRM) and includes all necessary information like bandwidth and QoS requirements. Furthermore, the SM as well as the RTM are informed regarding the supported RAT and frequency ranges. Depending on the requirements (reliability, transmission time, etc.) multi-connectivity can also be used, whereby this can be done in both reduced and duplex mode as well as across technologies [35]. The information about the assigned resources is then transferred via the RTM to the RAN. The RAN is then responsible for scheduling the individual applications or clients in conjunction with the MDMO, the 3GPP network MANO. The scheduling is then transferred to the radio access point (RAP).

2) TSN INTEGRATION

One of the major objectives of TACNET 4.0 is the integration of mobile radio communication systems into heterogeneous industrial networks. The key requirements and challenges are discussed in [36]. Figure 8 illustrates the integration based on the TACNET 4.0 architecture, which is compliant with 3GPP Release 16. In the integration architecture described in detail in [37], the 5G mobile network is represented towards the TSN network as a TSN bridge, which results in a transparent integration on user, control, and management plane. For this transparent integration, a TSN translator on UE side is introduced, which maps an Ethernet port on DCE side on a PDU Session within the 5G mobile network. On network side, another TSN translator makes sure that data arriving from DCEs is correctly forwarded to ports on the CN side, and vice versa. Furthermore, dedicated TSN control plane functions are introduced, which make sure that the 5G mobile network is correctly represented as a TSN bridge towards the TSN CNC.

On data layer, the above integration model allows for mapping uniquely an Ethernet port on a 5G mobile network connection, i.e., a PDU session. Based on the information from the CNC on the individual TSN streams, the 5G mobile network configures for each DCE a set of QoS flows, each characterized by a 5G QoS indicator (5QI). These 5QI match the different traffic classes that are used in a TSN network and selected using the Priority Code Point (PCP) field of the virtual local area network (VLAN) tag. For each 5QI, a packet delay budget within the 5G mobile network is defined that must match the maximum bridging delay reported to the CNC. Furthermore, based on the information provided by the CNC on the expected arrival of frames on DCE or CN side, and on the expected delivery of frames, the 5G mobile network can derive the resources required, i.e., by utilizing configured grants for uplink communication (in order to reduce the required overhead for requesting resources) and semi-persistent scheduling in downlink communication.

On control plane, the 5G mobile network has to process the information about connected devices, e.g., by evaluating the Link Layer Discovery Protocol (LLDP) information provided by DCEs. This information can be augmented with information specific to the 5G mobile network, e.g., subscriber information of the connected UE or location of the UE. This information would be provided to the CNC in order to perform the network discovery. This implies that each DCE offering an Ethernet port using the TSN translator should also support LLDP in order to provide the connectivity information required. The interaction between 5G mobile network and CNC is based on snmp and mib exchanged between both. The most relevant MIBs are Bridge-MIB (RFC 4188), Interface-MIB (RFC 2863), and LLDP-MIB (IEEE 802.1AB). The respective information includes the number of connected ports (represented by TSN translators) as well as port-specific information, VLAN capabilities, performance related information, as well as potentially SNMP traps in order to inform the CNC about changes of the 5G mobile network.

In addition, the 5G mobile network has to support synchronization using the generalized Precision Time Protocol (gPTP). For this, the individual Ethernet ports on DCE and CN side have to support the corresponding message exchange required for the synchronization. On control plane, the 5G mobile network has to make sure that the difference between the time applied by the TSN network (and provided by the

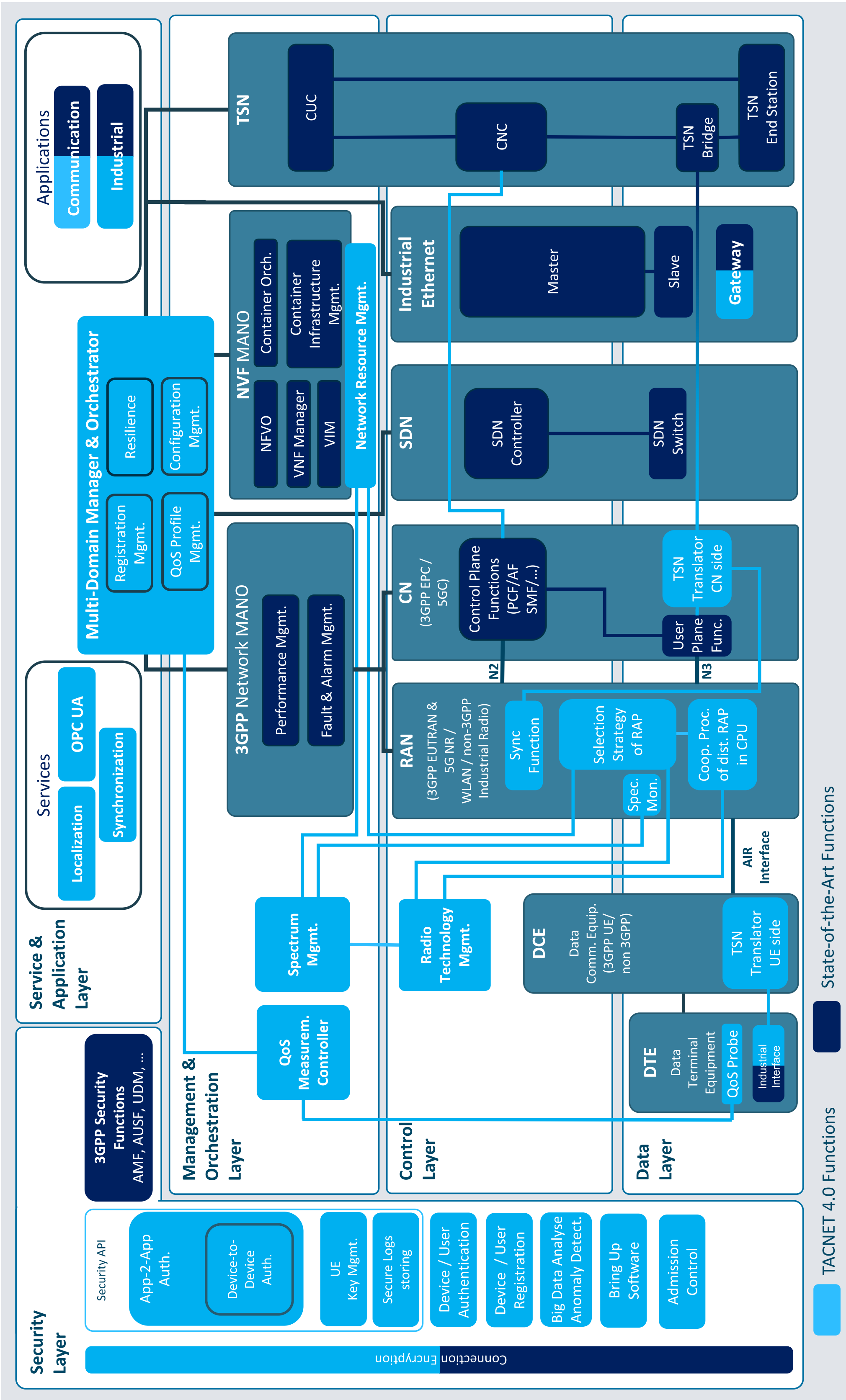

FIGURE 8. Full TACNET 4.0 Architecture including Interfaces.

master clock) and the time used by the 5G mobile network is tracked. The difference between both is needed, particularly by the DCEs, to apply the correct TSN time. One possible method for synchronizing 5G UEs with gPTP using the Reference Broadcast Infrastructure Synchronization (RBIS) protocol was investigated in [38]. RBIS is also a potential solution to acceptably synchronize UEs for installations that belong to 3GPP Release 15 and less.

Using this integration architecture, it is possible to flexibly cluster mobile equipment to TSN bridges specific to their usage and deployment. For instance, equipment which is used for local communication within a (small) automation cell may be grouped to one TSN bridge and the corresponding user plane processing may be located close the automation cell in order to localize traffic and minimize latency. On the other hand, mobile equipment such as automated guided vehicles (AGVs) may be grouped in larger TSN bridges, which contain a larger number of base stations and therefore, the mobility of the AGVs would be hidden from the CNC. Within the same 5G mobile network multiple such TSN bridges can co-exist and can be deployed specific to a use case. A key role to manage and orchestrate the resources for this flexible deployment is taken by the MDMO, which is detailed in the following section.

3) MULTI-DOMAIN MANAGER & ORCHESTRATOR (MDMO)

In nowadays 3GPP networks the establishment and configuration of logical links is usually triggered by users at UE side. This is not feasible in an industrial environment where the UEs are hardly accessible. On the other hand in industrial applications, the configuration of logical network links is usually closely coupled to the programming of the application functions. This will not work in a hybrid network with 5G included, since the responsibility for network operation may be with another party and the industrial application might not have exclusive access to the network resources. Therefore the TACNET 4.0 architecture requires an entity dedicated to the management and orchestration of network resources.

The TACNET 4.0 architecture is characterized by various network domains at the lower layers. At the service and application layer, different QoS requirements of the industrial use cases and multi-tenancy need a specific handling of the control and user layer. Network slicing as a mean to join together vertical-centric services at the business and application layer, and network-centric services at the infrastructure layer [12] is an enabling concept for the MDMO. The MDMO will define and provide network slice types that are tailored to the industrial QoS requirements and at the same time supervises the slice deployment which is specific to the control layers of the network domains. Thereby, it enables interoperability and seamless protocol integration on user and control layer. In this position, the MDMO also coordinates the distributed domain-specific management entities. The MDMO separates user, control and management layer functions and thereby follows the paradigm of SDN in order to allow the flexibility of network management and control according to the Industry 4.0 concept.

The MDMO comprises of the following functions.

- Registration Management: both devices and user applications need to be registered in order to access the TACNET 4.0 system. The specific registration steps are supervised and the registration information is maintained by this function.
- Resilience: this function provides the capability to detect and manage the most common network failures across the network domains in an autonomous way.
- QoS Profile Management: this function negotiates QoS requirements by application services and QoS provisions by network resources through mapping QoS models and utilizing QoS classes.
- Configuration Management: to achieve the required E2E QoS, the configuration of all involved domains will be done centralized in the higher level MDMO.

4) SECURITY & MONITORING

The convergence between IT and OT, as well as the introduction of wireless communication makes security an important topic, which until now has not had much relevance in industrial communication technology (ICT) [1]. Due to the requirements of Industry 4.0 use cases [5], standard methods known from the office environment (IT) cannot be applied. Furthermore, there are existing security mechanisms located at the OT like WirelessHART and ISA 100.11a that are considered. Similar to 5G security mechanisms these technology mechanisms are necessary but not sufficient conditions to meet the security challenges and requirements of the considered use cases. Especially a highly flexible, adaptive and largely automated security management in real-time (partly latencies of $\leq$ 1 millisecond) with ever-changing environmental parameters and threats is targeted. Furthermore, operational security and safety measures have to be predominantly preventive (rather than reactive) and ensure the automated integration of the latest capabilities of multidimensional analytics, threat intelligence and digital assistance systems into the everyday expert dialogue for well-informed target-performance difference analysis and decisions to be made.

The experiences and findings showed that in order to achieve the highest reliability and trustworthiness without compromising the performance, the security conception process must follow the "security by design rules" and accompany the development of new solutions from the beginning throughout the entire life cycle. This is consistent with the security strategy in GAIA-X, where security by design was also identified as the most advisable approach [25].

Therefore, threat modeling workshops were already conducted at an early stage of the TACNET 4.0 project, confirming the confidence that this is the preferred way to receive documented assessed risks and appropriate security measures for each considered and protected element and data flow. Recently it has also been realized that the properties of safety, security and privacy are not isolated, but often correlate and require integrated measures and approaches.

After defining the concrete security requirements and constraints, the basic security processes were created and their dependencies presented in sequence diagrams to provide an adequate design for trusted entity and certificate management. Therefore, the corresponding units are device registration, user registration, admission control, device authentication, and user authentication, where each of these components were included in the security layer of Figure 8.

Furthermore, the UE key management is in control of the usage of cryptographic keys stored in the UE's secure element. Some keys might be used for certain applications or purposes only, such as decryption and signing. The app-to-app authentication establishes a secure channel between two applications. For example, this can be an application located on the UE and the corresponding application running in the edge cloud. It uses the underlying device-to-device authentication that establishes a secure channel between two devices using the keys stored in the secure elements. The secure logs provide access to a secure logging facility that stores logs guaranteeing non-repudiation, i.e. an entity cannot claim that it has not written the corresponding log entry. Finally, the connection encryption function encrypts the connection either on an application level in an E2E fashion, or uses the encryption functionality offered by the individual physical connections. Additionally, the 3GPP security functions like access and mobility management function (AMF) that is responsible for 3GPP registration management, unified data management (UDM) that is in charge of the 3GPP authentication key agreement (AKA) authentication credentials, and authentication server function (AUSF) that are supporting authentication for 3GPP and untrusted non-3GPP access, are located in the security layer and can be applied by the CN.

By analyzing meaningful correlations with big data analytics methods, the reliability of use cases can be further increased by improving the continuous level of security.

As a basis for this, QoS probes were designed as hardware- and software-based units and are integrated in each DTE. For instance, this could be a robotic system, such as an AGV, including the secure element. Due to minimizing the initiated additional data load on and between the different layers and to balance it with conducted big data analytics or anomaly detection on the management & orchestration and security layer, smart pattern matching functionality is planned to realize on the QoS probe that is located in the user layer.

By analyzing the communicated packet information, the QoS probe allows to verify if the required QoS and the correct implementation of required security and privacy measures are fulfilled. The associated QoS measurement controller automatically initiates active and passive measurements continuously conducted by the QoS probe.

These get forwarded via the MDMO to the big data analysis & anomaly detection service. If this data is correlated with other collected safety-related QoS data from fault, configuration, accounting, and performance management, the data measured by the QoS probe, can be an essential support for predictive pattern recognition and anomaly detection in future 5G and Industry 4.0 scenarios.

Thus, the represented big data analytics & anomaly detection unit could develop to one of the success factors and important comprehensive use cases to exploit the productivity and other benefit potentials through deep monitoring.

V. EVALUATION STRATEGY

In order to ensure that the architecture developed in TACNET 4.0 also finds use outside the project, the interest of users must be gained. To achieve this acceptance, several points have to be addressed. First, it must be shown that the KPIs of the use cases, to which the architecture is tailored, can be fulfilled. This will be shown at the end of the project by a combination of simulations and selected testbeds in order to be able to make a realistic conclusion.

Another point to be verified, are the economic benefits. For this purpose, deployment strategies were created on the basis of specific scenarios in order to carry out suitable installations depending on the size and requirements of the company. In order to make the architecture feasible, care was also taken to make it modular. Due to the fact, that standardized interfaces are used and new interfaces are included in standards [27], it is possible to use only required parts of the architecture.

A SME planning to expand its existing system by using 5G to implement individual new use cases, for example, has the option of operating their own 5G system using predominantly 5G equipment out of the box (non-public network) or having network slices operated by a network operator (virtual non-public network).

For large enterprises, on the other hand, different migration and integration strategies are recommended.

VI. CONCLUSION

Within this paper, we have introduced the TACNET 4.0 architecture that enables Industry 4.0 use cases by the integration of 5G in industrial environments. Furthermore, representative use cases were selected as the basis for the design of the architecture in order to address a possibly heterogeneous range of requirements. It turned out, that already known approaches like IIRA, RAMI 4.0, GAIXA-X, ETSI oneM2M, 3GPP, or even 5GPPP's 5G NORMA project do not offer suitable solutions for this problem. For this reason, we have developed a novel architecture specifically tailored to the requirements defined in TACNET 4.0. Based on a five-layer approach, the TACNET 4.0 architecture allows the integration of 5G, TSN, SDN, and IE. Additionally, a concept for a RTM, the integration of 5G and TSN, a centralized manager for guaranteeing E2E QoS, and an innovative security strategy have been proposed.

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MICHAEL GUNDALL received the M.Sc. degree in electrical and computer engineering with a specialization in automation and control from the Technical University of Kaiserslautern, Germany, in 2017, where he is currently pursuing the Ph.D. degree in electrical and computer engineering.

Since 2017, he has been working as a Research Assistant with the German Research Center for Artificial Intelligence GmbH (DFKI), Kaiserslautern. His current research interests include in the area of industrial communication systems and the virtualization of automation systems.

MATHIAS STRUFE received the Diploma degree in communications engineering from the University of Applied Science, Kaiserslautern, Germany, in 2010, and the B.Eng. degree (Hons.) in electrical and electronic engineering from the University of East London, U.K.

Since his start at the German Research Center for Artificial Intelligence GmbH (DFKI), he was involved in several EU and national funded research projects with topics on AI-based network management.

HANS D. SCHOTTEN (Member, IEEE) received the Diploma and Ph.D. degrees in electrical engineering from the Aachen University of Technology RWTH, Germany, in 1990 and 1997, respectively.

He held positions, such as a Senior Researcher, a Project Manager, and the Head of research groups at the Aachen University of Technology, Ericsson Corporate Research, and Qualcomm Corporate Research and Development, respectively. At Qualcomm, he was the Director of Technical Standards and a Research Coordinator of Qualcomm's participation in national and European research programs. Since 2007, he has been a Full Professor and the Head of the Chair for Wireless Communications and Navigation, Technical University of Kaiserslautern. Since 2012, he has also been the additionally Scientific Director of the Intelligent Networks Research Group, German Research Center for Artificial Intelligence. His topics of research interests include wireless communication and 5G.

PETER ROST (Senior Member, IEEE) received the Ph.D. degree from Technische Universität Dresden, Dresden, Germany, in 2009, under supervision of Prof. G. Fettweis, and the M.Sc. degree from the University of Stuttgart, Stuttgart, Germany, in 2005.

He has been with the Fraunhofer Institute for Beam and Material Technologies, Dresden, Germany, IBM Deutschland Entwicklung GmbH, Böblingen, Germany, and NEC Laboratories Europe, Heidelberg, Germany. Since May 2015, he has been a member of the Standardization and Research Laboratory, Nokia Bell Labs, Munich, Germany, where he is currently with TM of the German BMBF project TACNET 4.0, led the 5G Industrial IoT Testbed at Hamburg Seaport, and also leads internal research and standardization work on the Industrial IoT. He has been involved in several European projects as a Project and a Technical Manager, and in IEEE and 3GPP standardization. He published more than 50 scientific publications and he is author of multiple patents and patent applications. He also serves as a member of VDE ITG Expert Committee Information and System Theory.

CHRISTIAN MARKWART received the Dipl.-Ing. degree from FHS Wiesbaden, Germany, in 1985.

Since then, he has been working in varying positions dealing with end-to-end aspects in public and private networks. He is currently involved as a Senior Research Engineer with the Nokia Bell Labs Standardization Research Laboratory. His current research interests include wireless connectivity for the Industrial IoT and new vertical sector players, especially spectrum licensing and sharing methods like Citizens Broadband Radio Service (CBRS) and evolved Licensed Shared Access (LSA), as well as new wireless end-to-end communication services based on Time Sensitive Networking (TSN) via a 3GPP 5GS. Related to this work he contributed to the research projects METIS, METIS-II, CoMoRa, and TACNET 4.0 and standardization in WInnForum, ETSI RRS, and 3GPP SA2.

ROLF BLUNK received the Dipl.-Ing. in degree communications technology from Berlin, Germany, in 1978.

He was responsible for the regional security business development at SIEMENS for more than ten years. He is currently a Co-Founder and a member of the Security Forum in Bremen (BremSec) and the IFIT-Free Institute for IT Security e.V. (also function as an Advisory Board). He also heads the working Group Security by Design, Federal Association for IT Security in Germany, TeleTrusT. At OTARIS, he is also responsible for and accompanies research and development projects and works on the 5G architectural models as part of the TACNET 4.0 research project.

ARNE NEUMANN received the Dipl.-Ing. degree in electrical engineering from Otto-von-Guericke-University Magdeburg, Germany, in 1993.

He was busy in the field of development, standardization, and certification of industrial communication systems with ifak e.V. Magdeburg, Germany. In 2015, he joined the Institute Industrial IT (inIT), Lemgo, Germany, where his research domain is about QoS aspects in hybrid industrial networks. He has been the Deputy Chair of the working Group Validation and Tests in 5G-ACIA, since 2018.

JAN GRIEBACH received the B.Eng. degree in information- and electrical engineering from the Hamburg University of Applied Sciences, Hamburg, Germany, in 2014, and the joint M.Sc. degree in microelectronic systems and joint master's programme from the University of Applied Sciences, Heide, Germany, and from the Hamburg University of Applied Sciences, in 2017.

Since 2017, he has been working with NXP Semiconductors Germany GmbH, as a Software Developer in NXP's Cooperative Innovation Projects Team. In 2018, he switched to the NXP's newly founded Industrial Competency Center.

MARKUS ALEKSY received the degree in management information systems and the Ph.D. degree from the University of Mannheim, Mannheim, Germany, in 1998 and 2002, respectively, and the Ph.D. degree in information science from Tokyo Denki University, Tokyo, Japan, in 2007.

He lectured with the University of Mannheim, Germany, and Queen's University, Canada. He is currently a Senior Scientist with the ABB AG Corporate Research Center, Ladenburg, Germany. He is the author or coauthor of more than 100 research articles. His research interests include analysis, design, implementation, and evaluation of mobile and networked systems.

DIRK WÜBBEN (Senior Member, IEEE) received the Dipl.-Ing. (FH) degree in electrical engineering from the University of Applied Science Münster, Germany, in 1998, and the Dipl.-Ing. (Uni) degree and the Dr.-Ing. degree in electrical engineering from the University of Bremen, Germany, in 2000 and 2005, respectively.

He currently is a Senior Researcher Group Leader and a Lecturer with the Department of Communications Engineering, University of Bremen. His research interests include wireless communications, signal processing, multiple antenna systems, cooperative communication systems, and channel coding. He has published more than 130 articles in international journals and conference proceedings. He is a Board Member of the Germany Chapter of the IEEE Information Theory Society and a member of VDE/ITG Expert Committee Information and System Theory.