Cross-domain 5G Network Management for Seamless Industrial Communications

Christian Mannweiler, Lars Christoph Schmelz
Nokia Networks, Munich, Germany
{christian.mannweiler,christoph.schmelz}@nokia.com

Simon Lohmüller, Bernhard Bauer
University of Augsburg, Germany
{lohmueller,bauer}@informatik.uni-augsburg.de

***Abstract*—Emerging scenarios of vertical industries, such as, adaptive manufacturing, cooperative autonomous driving, and real-time logistics demand for seamless communication among mobile entities, among them ground conveyors, user terminals, cars, or sensors. In practice, this leads to challenging requirements in terms of latency, bandwidth, availability, reliability, etc. that current mobile communications technologies, including cellular networks and IEEE 802-based solutions, do not fully account for. When deployed individually, neither of them fulfills the broad range of requirements, whereas a coordinated co-deployment suffers from the lack of efficient network management solutions as well as from insufficiently defined operating and owner structures for these mixed system deployments. Therefore, this work proposes a concept for an intelligent cross-domain 5G network management system and related optimization functions. In particular, the design of a cognitive, joint management of mobile industrial and cellular networks is outlined. Further, cognitive methods and virtualization techniques are motivated as major enablers. Advantages include an operator-grade network management of local industrial networks as well as a seamless integration with cellular networks. Following 5G design principles, the suggested network management system is also extensible to emerging radio access technologies (RATs) in the 5G context.**

I. Introduction

Scenarios of future industrial systems are consistently characterized by a high degree of digitization in manufacturing. Besides increased computing resources (e.g., on the factory floor), this so-called fourth industrial revolution ("Industry 4.0") is expected to bring along seamless connectivity between machines, sensors, ground conveyors, trucks, and other devices, including mobile work terminals [1]. Concepts such as the Internet of Things (IoT) or the Industrial Internet will facilitate a big leap in further automating processes across the entire value chain in many industries. However, current industrial wireless networks, such as IEEE 802-based technologies, Bluetooth, as well as proprietary technologies, suffer from several drawbacks. Among others, their high level of customization towards specific application domains goes along with limited flexibility. Due to the high vertical integration of such siloed solutions, they also lack the capabilities for both reasonable interoperability and joint, cross-technology Operations, Administration, and Maintenance (OAM) [2]. Moreover, an interaction of industrial wireless networks with cellular networks, e.g., with respect to seamless roaming, requires high manual configuration effort or is not possible at all. Usually, devices need to be equipped with two radio interfaces for local and cellular connectivity. Finally, partially adapted 4G cellular solutions, such as small cells with reduced coverage, have not gained major popularity in industrial environments since they were not able to meet requirements, e.g., low latency [3]. As a consequence, Industrial Internet use cases have been included in the development of 5G mobile networks in very early phases in order to make next generation cellular solutions more attractive for vertical industries. These requirements include, among others, low latency, increased reliability and robustness, and application of proven SON (Self-Organizing Network) techniques in industrial networks. Nevertheless, any future-proof OAM system will need to accommodate legacy technologies.

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Therefore, the objective of this work is to design a cross-domain system for a joint cognitive, automated management of heterogeneous industrial wireless networks and cellular networks. The approach is to adapt current mobile OAM solutions in such a way that industrial networks are integrated. This will be realized by utilizing different enablers such as Network Function Virtualization (NFV) for provisioning Network as a Service (NaaS), cognitive algorithms for industrial networks, as well as algorithms for autonomic management of network functions.

The remainder of this paper is structured as follows. Section II depicts the relevant use cases and according requirements. In Section III, an overview on related work is given. Section IV presents the concept for a cross-domain OAM/SON system, including key innovations, technological enablers, and a qualitative evaluation. Section V concludes the paper.

II. Use Cases and Requirements

A. Industrial Automation and Control Systems

Industry 4.0 [1] refers to the fourth industrial revolution which is driven by digitization and the merging of manufacturing systems with information and communication technologies, transforming them into so-called Cyber-Physical Systems (CPSs). Besides the aforementioned wireless technologies, current manufacturing environments also rely on Industrial Automation and Control Systems (IACSs) [4]. Manifold use cases exist that motivate a tighter integration of industrial communication technologies, e.g., those issued by the German Industrie 4.0 Working Group [1]:

1) Networked Manufacturing: The goal is to enable a flexible composition of production resources to allow for highly customized factory output. State, location, capabilities of individual components across the entire value chain can be communicated in real-time, and production planning and control systems can react accordingly.

2) Self-organizing Logistics: Extending the concept of networked manufacturing to the logistics domain, continuous traceability of raw materials and semi-finished goods allows for a dynamic and self-organized adaptation (e.g., commissioning cycles, just-in-time deliveries) of processes in intra- and inter-factory logistics.

3) Intelligent Maintenance Management: Unexpected machine downtime and associated high costs are avoided by intelligently determining maintenance intervals. This includes performance monitoring for flexible scheduling of downtime to execute planned repair or replacement work.

In this context, the seamless interoperability of IACS with wide area networking infrastructure is a major requirement. A minimum level of integration realizes an interconnection on the data plane. A tighter coupling of control plane and joint management plane methods facilitate a more efficient end-to-end utilization and management of heterogeneous networks.

B. Machine-to-Machine Communications

Machine-to-machine (M2M) communications is expected to represent a substantial part of 5G Industrial Internet traffic. Massive Machine-Type Communications (mMTC) shall enable big data analytics and includes massive deployments of devices producing very high traffic volumes [3]. Examples include low-cost battery-powered sensors and actuators in public spaces, industrial environments, and smart homes or remotely controlled utility meters. Assuming 10 to 100 of such connected devices per human user, 5G systems have to provide connectivity solutions capable of scaling for several billions of devices. Ultra-reliable Machine-Type Communications (uMTC) comprises use cases requiring the provisioning of a given network service with very high probability. This includes use cases where low delay is a critical factor, such as remote driving and haptic communication enabling remote work in, e.g., hazardous environments. In conjunction, mMTC and uMTC stipulate challenging requirements: Latency should be in the order of magnitude of 1ms, protocol scalability should not fall below 80% for 300,000 devices per access node and coverage shall be at 99.9% [3].

C. Vehicular Communications

Information exchange among vehicles (V2V) and between vehicles and infrastructure (V2X) enables cooperative driving, increased safety, improved traffic flow, as well as reduced fuel consumption and emissions. Moreover, the infrastructure can be utilized for delivering infotainment services to vehicles. However, the highest impact on industrial environments will stem from V2V and V2X enabling autonomous driving. According requirements therefore are particularly safety-critical and include an end-to-end latency of less than 5 ms for 99.999% of all transmissions, supported vehicle speeds of up to 500 km/h as well as a detection range of up to 1 km [3].

III. Related Work

A. Management of Mobile Networks

The concept of SON plays a crucial role for automated FCAPS (fault, configuration, accounting, performance, security) management of cellular networks. The first generation of SON functions was developed as independent closed-control-loop algorithms dedicated to a single radio access technology (RAT) - with a focus on 4G. Due to their attractiveness for operators, they have also been retrofitted to 2G and 3G. Such functions have been developed, e.g., within the FP7 research project SOCRATES [5]. Second generation SON functions have been able to cope with increased network heterogeneity by working across multiple RATs (2G, 3G, 4G, and, to some extent, WiFi) and across hierarchical layers (e.g., macro and micro cells) within these RATs, e.g., by utilizing instrumentation of individual SON functions according to operator policies [6]. However, the focus of the majority of these activities has been confined to 3GPP-based use cases. The Unified Management Framework (UMF) of the FP7 UniverSelf project [7] aimed at a more abstract framework that generalized the management functionality towards coordinating multiple functions/algorithms from different access networks. However, all of the aforementioned concepts and implementations lack a concept for the integration of three important ingredients: a consistent approach for automation of SON functions, the inclusion of cognitive algorithms enabling such automation and, finally, the applicability in a cross-domain (cellular and industrial mobile networks) setup.

B. Management of Industrial Wireless Networks

Wireless networks deployed in industrial environments frequently utilize IEEE 802-based solutions (WiFi, ZigBee, WirelessHART), Bluetooth or even proprietary radio technologies. Usually, their specification is limited to physical, data link, and networking layers, whereas OAM is not covered. As a result, FCAPS either is not available at all or has only been implemented in a rudimentary or application-specific way. Examples include coverage planning and capacity optimization [8], interference management [9], or media-independent handover frameworks [10]. However, no generalized frameworks and standards comparable to cellular OAM/SON exist.

IV. Concept for Cross-domain Network Management

A. Design Approach to Network Management

The use cases described in Section II bring along two major challenges. First, for full support, they require both local and wide area networking (LAN and WAN). According connectivity solutions have to be configured and controlled in coordination with each other to allow for a flawless operation (*horizontal alignment*, cf. Figure 1). Second, the use cases exhibit heterogeneous sets of quantitative and qualitative requirements, which in turn demand for a tailored end-to-end network service per use case, i.e., the right set of network functions at the appropriate nodes of the infrastructure. However, for reasons of optimizing total cost of ownership, it is not feasible to deploy dedicated infrastructure for each network service. Rather, multiple network services should utilize the same underlying hardware. This concept, also referred to as *network slicing* [11], calls for a *vertical alignment* among the deployed network services to account for the interdependence resulting from the shared hardware utilization.

From the network management perspective, the horizontal alignment requires a set of functions that operate on a cross-domain level, i.e., reconciling SON functions of both industrial wireless as well as cellular networks. With respect to the vertical alignment, a hierarchy of SON functions has to be defined. While the distributed functions perform FCAPS on the "intra-slice" level, the higher level (centralized) SON functions perform according actions for the entire infrastructure, i.e., on the "inter-slice" level. Therefore, the allocation of decision-making authority to as well as the coordination between hierarchy levels are major design choices.

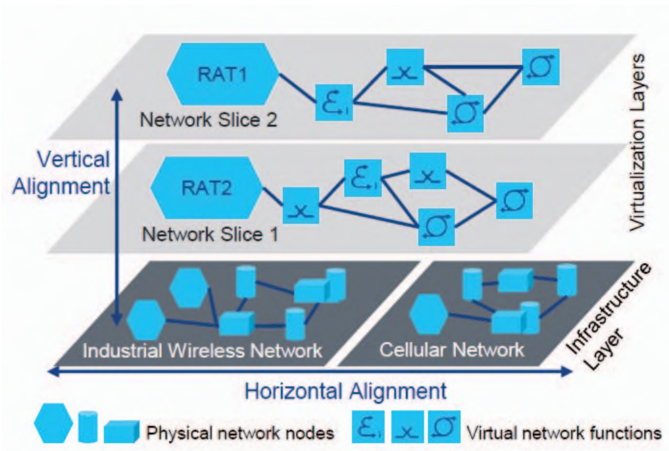

Fig. 1. Design Approach to Cross-domain Network Management

B. Technological Enablers

An OAM system that can cope with the complexity of multi-domain networks as well as multiple slices sharing the same infrastructure requires technological enablers for automation and cognitive behavior.

NFV [12] is one of the key paradigms in the design of 5G mobile networks. It comprises a full decoupling of application logic (i.e., selected "softwarized" network functions) from the underlying physical resources, such as data centers, switches, and, to a limited extent, radio base stations. In its full flavor, NFV makes available virtualized computing, storage, and networking resources in customized units and facilitates the NaaS approach including resource sharing across multiple slices and operators. This enables a flexible instantiation and composition of virtualized Network Functions (vNFs) and therefore the provisioning of multiple, isolated and use case-tailored network slices on the same network infrastructure, which is a significant advantage particularly for capital expenditures-intensive cellular networks. The model of a use case-specific slice is derived from the according requirements (QoS, security, reliability, etc.). Utilizing lifecycle management approaches like those defined by ETSI [13], network functions and end-to-end services can be instantiated, scaled in and out, upgraded, and terminated. The upgrading includes software upgrades and configuration changes of various complexity levels. As such, NFV and lifecycle management relieve network management from several basic tasks. However, a close coordination between the two systems is required.

Cognitive methods and *policy-based SON management* form the second group of technological enablers. Today's industrial communication systems can be characterized as isolated, vertically integrated solutions. A co-located operation of these systems, including a minimum level of interoperability between them, requires an OAM system that supports methods for the generation of adaptive, requirements-specific and context-aware rule sets or policies. Hence, SON management approaches (cf. Section III-A) need to be extended to exhibit cognitive behavior. Knowledge gained from data collection, information extraction, processing and analysis cannot only be applied within the same domain, but also across domains. Machine-learning methods exploit performance indicators from both network domains for recognizing error and security conditions, or outlier events such as fraud and can suggest according corrective actions [14]. The need for such tools becomes even more evident for the integrated management of industrial mobile networks and cellular networks. For the latter, sophisticated management systems already exist today. However, they need to be significantly re-designed in order to perform FCAPS in coordinated, cross-domain manner.

C. System Architecture

Figure 2 represents the architectural concept for a cross-domain OAM/SON system. On the lowest layer (*infrastructure layer*), it depicts the physical elements of the domains considered in this work, industrial wireless networks with heterogeneous networking technologies as well as cellular networks of different generations. Each of the domains host SON functions performing uncoordinated (isolated) configuration and optimization of the respective network. The middle layer (*virtualization layer*) contains an (unstructured) pool of virtualized resources. Effectively, this comprises a pool of general purpose hardware that can be used to deploy network functions in a more flexible and adaptive manner. Finally, the top layer depicts the business application (*network service layer*). It hosts multiple network slices that are composed by network management and orchestration functions according to the requirements of the addressed (business) use case. This includes slices for industrial communications (Industry 4.0 slice), but also specific slices for smartphone users (mobile broadband) or V2X communications. The outlined system can be realized in three fundamental development steps.

1) In the first step, while still separated on management and control plane, network domains interact on the user plane, e.g., for transferring data related to products or manufacturing processes. Existing techniques from cellular OAM are adapted to allow for setting up a basic connectivity between industrial and cellular networks.
2) In the second step, both domains are loosely coupled on both c- and m-plane level. This requires the definition of a few dedicated interfaces between the domain-specific OAM systems. This allows for a basic *horizontal alignment* of SON functions in industrial and cellular networks.
3) The final step comprises a cross-domain function that performs a joint optimization of the two domains. The required consistent end-to-end view of the two domains is realized by introducing an additional level of abstraction by means of applying virtualization techniques to the greatest possible extent. The overarching entity serves as central reference point for the according domain-specific SON entities. Besides

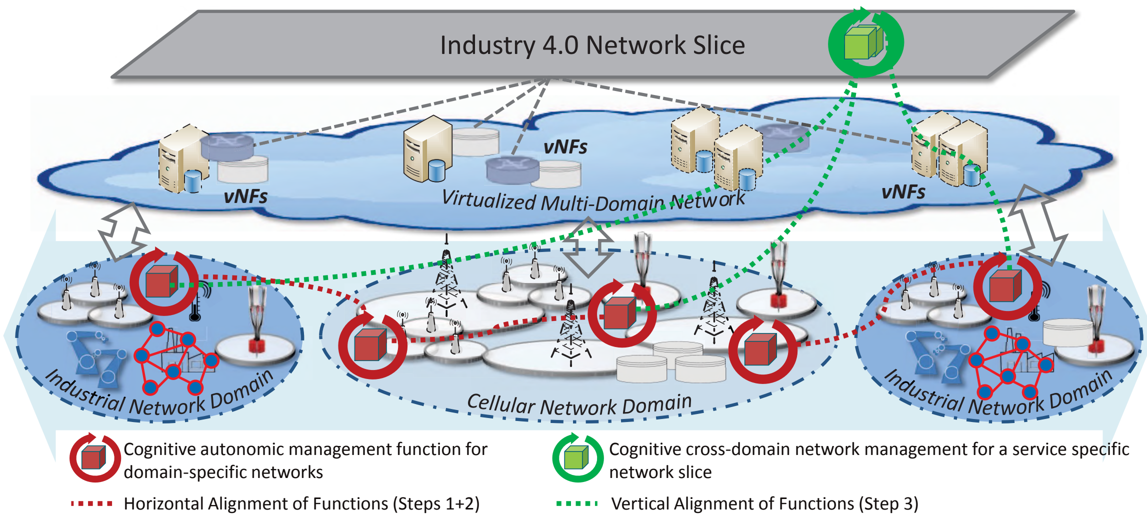

Fig. 2. System Concept for Cross-domain Network Management

realizing a comprehensive *horizontal alignment*, this enables a *vertical alignment* between multiple slices.

D. Design Challenges and Relevance to 5G

Due to the inherently heterogeneous technology landscape, the challenges in designing a cross-domain network management system are manifold. First, OAM methods for industrial networks are far less advanced than for cellular networks. In order to realize the discussed horizontal alignment, SON functions in industrial networks need to be brought to a level matching cellular SON functions. Second, it remains open to further study to what extent a multi-domain network can be represented as a virtualized network. With respect to the vertical alignment (which mediates between multiple slices utilizing the same infrastructure), the coordination between SON functions on different hierarchy levels comprises the third design challenge. As a minimum, the design has to consider SON functions solely in charge of bare-metal network elements from either domain, functions dedicated to vNFs, and, finally, SON functions mediating between multiple network services and the physical infrastructure. This last aspect is of particular relevance to the design of 5G mobile networks since addressing the requirements of vertical industries is among the top priorities of 5G. OAM solutions have to be able to cope with the heterogeneity of utilized radio network technologies and mixed bare-metal and virtualized networks.

V. Conclusion

This paper has presented a concept for an intelligent 5G network management system and related Self-Organizing Network (SON) functions for heterogeneous wireless networks. In particular, a system concept for the cognitive, joint management of mobile industrial and cellular networks has been outlined. The necessity for such systems has been motivated by latest use cases in the context of industrial, machine-type, and vehicular communications. The proposed network management solution particularly addresses the requirements of vertical industries as outlined in forums such as the Industrial Internet Consortium or the Industry 4.0 Working Group. Further, this work has proposed a phased approach for the realization of a cross-domain OAM, where the final phase realizes a high integration level including a common c- and m-plane functionality. Advantages of the cross-domain management system include significantly improved Operations, Administration and Maintenance (OAM) as well as SON functionality for industrial wireless networks, seamless connectivity with cellular networks, and extensibility w.r.t. emerging 5G radio technologies.

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