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ABSTRACT

Following the Industry 4.0 vision of a full digitization of the industry, time-critical services and applications, allowing network infrastructures to deliver information with determinism and reliability, are becoming more and more relevant for a set of vertical sectors. As a consequence, deterministic network solutions are progressively emerging, albeit they are still bounded to specific technological domains. Even considering the existence of interconnected deterministic networks, the provision of an end-to-end (E2E) deterministic service over them must rely on a specific control plane architecture, capable of seamlessly integrate and control the underlying multi-technology data plane. In this work, we envision such a control plane solution, extending previous works and exploiting several innovations and novel architectural concepts. The proposed control architecture is service-centric, in order to provide the necessary flexibility, scalability, and modularity to deal with a heterogenous data plane. The architecture is hierarchical and encompasses a set of management platforms to interact with specific network technologies overarched by an E2E platform for the management, monitoring, and control of E2E deterministic services. Furthermore, Artificial Intelligence (AI) and Digital Twinning are used to enable network predictability and automation, as well as smart resource allocation, to ensure service reliability in dynamic scenarios where existing services may terminate and new ones may need to be deployed.

MobiHoc '23, October 23–26, 2023, Washington, DC, USA

ACM 978-1-4503-9926-5/23/10 $15.00
https://doi.org/10.1145/3565287.3617605

CCS CONCEPTS

• **Networks** → **Network services** → **Programmable networks; Networks management; Network monitoring;** • **Networks** → Network algorithms → Control path algorithms → Network control algorithms; Network design and planning algorithms; Network resources allocation;

KEYWORDS

Network Determinism, Predictability, Reliability, Time-sensitiveness, TSN, DetNet, RAW, Control Plane, Cross-domain

1 Introduction

With the advent of the latest generation of mobile networks and their opening to the vertical industry, innovative services and applications have been designed to exploit the newly developed network capabilities. A relevant example is represented by autonomous vehicles, industrial automation, Augmented Reality / Extended Reality (AR/XR), but also generic IoT applications, for

which audio and video streaming has become strongly time critical and demand for a network infrastructure capable to deliver information with guaranteed determinism and reliability at the same time.

Current available solutions are operationally limited and domain-bounded, both technologically and at administrative level. Time Sensitive Networking (TSN) from IEEE 802.1, described in Section 2, is a classic example. Nevertheless, even assuming that any network technology would offer somehow support for deterministic communications at the data plane, the possibility of provisioning and maintaining E2E deterministic services still remains a challenging management and control problem.

To fill this gap, this work proposes a flexible control plane architecture that exploits innovative elements such as Artificial Intelligence / Machine Learning (AI/ML), Digital Twinning (DT), timely and pervasive monitoring, and frictionless service orchestration. In the following, first we investigate the-state-of-the-art solutions used to build flexible architectures and enable determinism (Section 2) and propose a control plane functional architecture that aims to guarantee network time-sensitiveness and determinism across a multi-technology data plane (Section 3.1). To this end, the concepts of Management and Managed Entities (MEs) are introduced, discussing how they can be exploited to design a modular, flexible and scalable control plane architecture. Then, we describe the core concepts of our architecture enabling predictability and reliability (Section 3.2), and the methodology used to abstract and model a heterogenous (multi-technology) data plane as a seamless continuous network (Section 3.3). Finally, we conclude with a discussion on relevant directions for future work (Section 4).

2 State of the Art and Reference Architectures

The decomposition of management and control platforms into a set of well defined, loosely coupled, and not overlapped services, is an architectural design paradigm widely explored and adopted, also by standard organizations. The 5G System architecture defined by 3GPP is one of the most well-known service-based architectures (SBAs) [1]. Furthermore, 3GPP defines Application Programming Interfaces (APIs) to request, control, and delete a range of resources targeted at supporting vertical applications, i.e., via the Network Exposure Function (NEF).

In [2], ETSI proposes a network and service management architecture completely based on the concept of service as a means to provide one or more management functionalities. Specifically, the ETSI Zero touch network & Service Management (ZSM) group issues standards for defining the concept and the operations for closed-loop (CL) automation, which improves, among others, resource utilization and aims at achieving optimal service quality, also introducing advanced topics such as the governance and the coordination of multiple and concurrent CLs [3]. ETSI ZSM does not specify which technology or technique should be used to analyse data and take decisions. On the other way around, the ETSI Experiential Networked Intelligence (ENI) group makes a large use of AI-based processes to enable network and service management automation in its system architecture [4].

With respect to the network determinism and time-sensitiveness, IEEE TSN is one of the most mature proposals. It defines a set of standards to create a deterministic LAN (based on Ethernet) for time-sensitive data transmission, and in [5] it also includes the definition of a Control plane architecture. IETF Deterministic Networking (DetNet) [6] is working to extend determinism up to IP layer, however, a specific control plane architecture has not yet been defined. IETF Reliable and Available Wireless (RAW) [7] aims to extend the principles of DetNet to wireless networks, contributing to seamless networking by ensuring predictable and reliable wireless connectivity. Incorporating RAW into the control plane architecture makes it possible to procure predictable and reliable E2E communication across multi-domain data planes by enabling seamless integration between wired and wireless technologies. This integration promotes the development of a flexible control plane architecture that can be exploited by a wide range of applications and use cases.

3GPP has been working on cellular WLAN interworking since several years (starting back in 2002 in Release 6 [8]) considering it as an operational requirement of the next generation access technologies and proposing always more advanced architectures to better integrate Wi-Fi in cellular networks. The details of convergence aspects of a 5G system and different architectures (N3IWF, TNGF, TWIF) are described in [9]. A key challenge is seamless dynamic traffic steering across licensed, and unlicensed networks and a mechanism to guarantee E2E Quality of Service (QoS). Multiaccess Network slicing can be used to define QoS slices for both licensed and unlicensed bands and guarantee system level agreements (SLAs). In [10] AI-based network slicing is discussed for cellular systems. The same concept can be extended to multiaccess and integrated with 5G multiaccess architecture.

In addition to standards, several recent papers deal with the decomposition of management and control planes. For instance, [11] introduces a service decomposition method for multimodal data exchange scenarios; [12] enhances the state of the art of SBA, [13] elaborates on the programmable data plane concept in industrial domains, and [14] follows the green-networking concept by introducing in networks features related to energy consumption.

Several EU funded projects also touched upon the topics highlighted above. For instance, VERGE [15] focuses on applying AI methods to evolve the 5G architecture towards 6G and HEXA-X [16] provides a comprehensive set of enhancements and proposals expected in forthcoming 6G networks.

3 AI-Driven Control Plane

3.1 Service Centric Approach

Creating E2E deterministic services based on a combination of network technologies requires a control and management plane that is modular and extendable to new network technologies. As individual standards and solutions for determinism have been evolving separately, there are significant differences in terms of

deploying and managing a service in each of them. Therefore, it is desirable to separate the complexity of dealing with specific technologies from the concern of creating and sustaining E2E services. A proper separation of technology management concerns from E2E service management concerns enables to extend the scope of E2E over new technology domains without impacting other technologies or the E2E capability.

The requirement on modularity and thus the separation of concerns motivates a hierarchical management design with (1) domain abstractions that provide encapsulation of deterministic mechanisms specific to each technology, and (2) an E2E service management scope that leverages domain abstraction to compose cross-domain services. This approach is in-line with the zero-touch network and service management architecture principles. In this strategy, the managed entities are network segments of a given technology (e.g., 3GPP, IEEE 802.1, IETF DetNet), which are supervised by a technology specific Management Domain (MD). This MD is specialized in handling the underlying network segment's Control/Management (C/M)-plane APIs and assure that part of a cross-domain E2E deterministic service falls within the confines of the domain. Accordingly, the technology-specific MD's role is to create deterministic services within the boundaries of the technology domain and adapt the domain's configuration to the service demands and dynamic network conditions. This MD consists of multiple Management Services (MS) that provide enablers of autonomous domain operation, such as network and service observability through measurement collection; exposure and abstraction of the domain's topology, deterministic control capabilities, resources; and domain level service assurance based on the domain's data plane mechanisms related to resource provisioning and QoS management. The MSs within the technology-specific MD are integrated via an SBA to create a modular composition of domain specific services that can be adapted to the capabilities of the underlying network technology. The set of MSs belonging to a MD is called Management Function (MF). Interactions between services are depicted in Fig.1.

Considering the E2E chain, there is an E2E MD that consists of the MSs responsible for the E2E deterministic services, which are crossing multiple network segments and terminated by endpoints (e.g., devices or cloud applications) that are attached to different network technologies. The E2E MD also consists of multiple MSs that collaboratively provide E2E service assurance capabilities, such as: (1) path computation across domains based on the available domain-specific topology, capability and resource matrix; (2) planning each domain's contribution to the E2E service quality in terms of delay budget, jitter cancellation, resiliency and other QoS metrics; and (3) dynamically resolving (predicted or detected) conflicts during service assurance (e.g., re-balancing the domain specific delay budgets to cancel the impact of one domain's delay build-up by enforcing stricter targets in an adjacent domain). The E2E MD is also the entry point to the definition of new services.

3.2 Reliability and Predictability Pillars

As AI/ML methods are becoming essential pillars for the

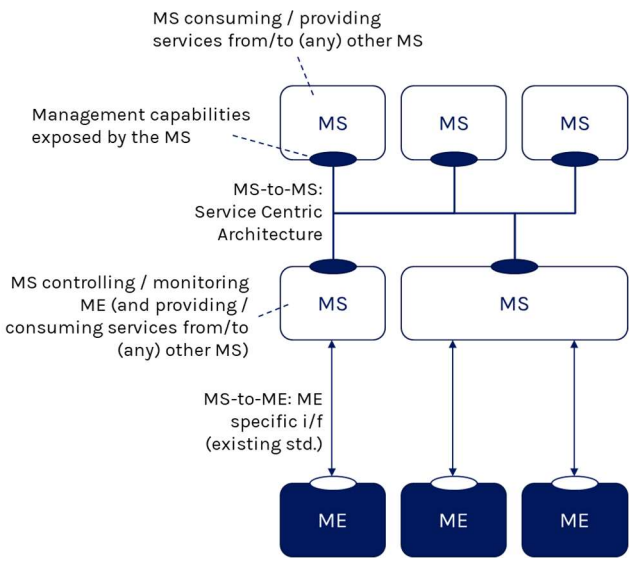

Figure 1: Service-centric architectural approach interactions

development of effective and efficient network services, three main challenges arise, i.e., how to: (1) add required computational resources (namely, CPU/GPU and memory) to AI/ML models; (2) reliably collect the data to be fed as input to such models, especially during the training phase; (3) make the overall AI/ML-pipeline sustainable from the energy consumption point of view.

We argue that an essential approach to adequately address (1) and (3) is to leverage distributed learning, which allows for the exploitation of computational resources owned by different types of network nodes and devices. Although distributed learning undoubtedly requires transferring information between nodes hosting different portions of an AI/ML model, hence some communication cost, computational resources are often the bottleneck for the training and execution of AI/ML models. It follows that being able to cluster network nodes and let them collaborate towards the execution of an AI/ML operation may bring significant benefits in terms of latency and energy consumption associated with the task. In this context, it is worth noticing that different distributed learning paradigms should be considered, and possibly combined, such as federated learning, sequential learning [17], and split learning [18].

Regarding (ii), it is of key importance for model training to combine real-world data, which can be gathered through experiments, with data that can be obtained through a DT of the network system. Moreover, we envision further enhancing data collection through data generation approaches, developing new methodologies that can enhance and customize the methodology proposed in [19] to the relevant network and application scenarios and domains. Data generation can indeed well complement real-world as well as DT-enabled data collection, at the cost of executing ML models devoted to this specific scope, which may lead to increased energy consumption. It is therefore critical to assess how learning can be performed by balancing the

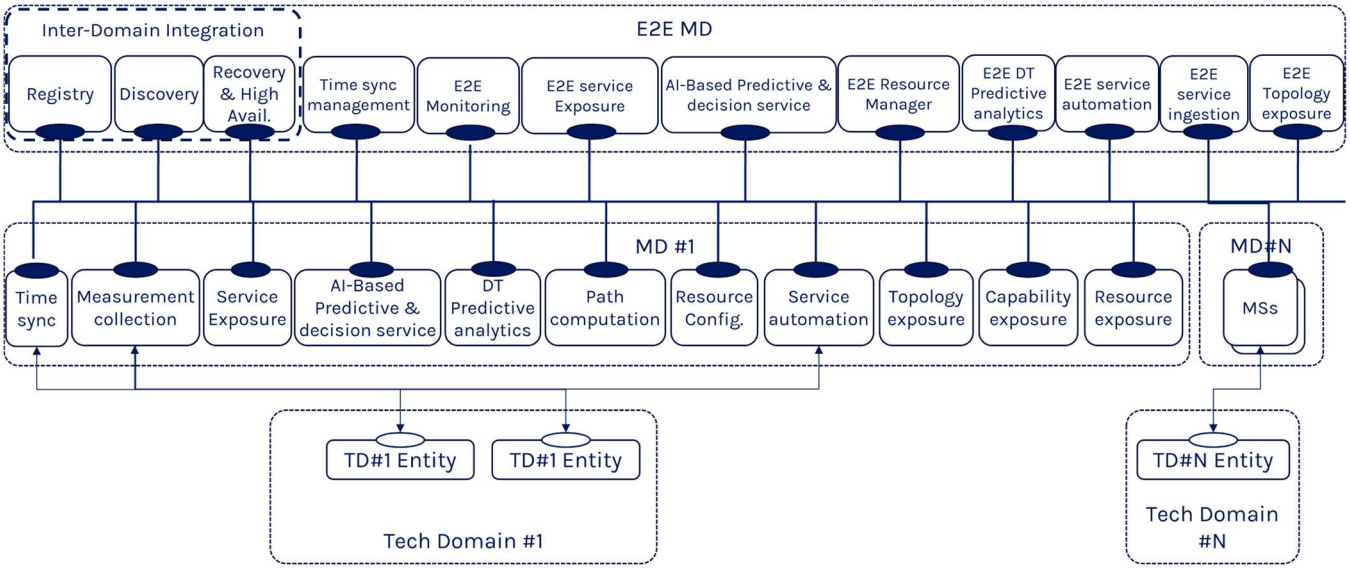

Figure 2: Example of hierarchical control plane architecture with related MSs

aforementioned three approaches to data collection, optimally trading off the quality level of the data with energy, computational, and networking resource consumption, depending on the type of AI/ML model to be trained or pre-trained (e.g., a Deep Neural Network vs. a reinforcement learning based model). In addition to data collection, the DT can also be used for modelling the network and estimating the performance at provisioning time, not only for the new service but also for the ones already deployed [20].

This is particularly important when the service to be deployed is sensitive to delay, i.e., TSN, in the presence of best-effort (BE) services, as shown in [20]. As a consequence, it is of paramount importance to develop accurate DTs for the different technological domains, e.g., 3GPP, Wi-Fi and packet, so that the performance of E2E services can be estimated. In addition, the applications of DTs include not only service provisioning, but also failure management, device configuration and simulation, as shown in [22].

To enable the automated creation of deterministic E2E services in a hierarchical management design where technology-specific and E2E MFs coexist, dynamic network control and frictionless inter-domain orchestration, that is, the capability of orchestrating E2E services across different and heterogenous domains, seamlessly and without conflicts, need to be ensured. At the same time, reliability and predictability aspects must also be guaranteed to meet the deterministic nature of the services. Considering these requirements and exploiting the architectural framework proposed in Section 3.1, a specific combination of several MSs in technology-specific and E2E domains is proposed as the most suitable option to enable the control, orchestration, and monitoring as part of a specific control plane solution (see Fig.2).

The MF associated to each technological domain follows a service-based approach to implement the set of functionalities (i.e., MSs) that enable the control, management and orchestration of such domain from the E2E level. To achieve this, the exposure of domain characteristics needs to be enabled first.

In particular, MSs responsible for collecting information related to the topology of the underlying domain, its resources and their capabilities (with a focus on the ones critical for deterministic service provisioning) are needed. Additionally, a service exposure MS is also required to share high-level information of specific service conditions. To enable this exposure, these MSs rely on the control APIs provided by each technological domain to compose a view of the data plane that can be used for intra-domain service computation as well as to expose the domain information to the E2E MF.

The exposure MSs enable the service computation (through the path computation MS) and configuration (by means of the resource configuration MS) at the domain MF. The management of the active services is realized thanks to the measurement collection MS. The telemetry provided by this MS is used to feed the DT and AI-based decision MS, which participate in the control loops implemented at domain level. Such loops are orchestrated by the service automation MS, addressing service fulfilment, assurance and termination stages. Finally, a MS dedicated to provide time synchronization across the domain is required, as the presented control plane focuses on providing support for deterministic services.

From the E2E perspective, to achieve the multi-domain deterministic service configuration and management, the E2E MF follows a similar approach. To collect the underlying domains' topological and resource information, a set of exposure services are needed. Some degree of abstraction is essential, first, to deal with the exposure limitations posed by the domains from an administrative point of view and, second, to keep the scalability of the system. Along the same line, a monitoring MS is needed to collect telemetry data and feed at the E2E level the DT and the AI-based decision MS that participate in the E2E control loops. With regards to the E2E service provisioning, a North-bound interface is needed to receive the service requests. This is implemented by the E2E service ingestion MS, which receives and interprets the intents

coming from users and/or operators. Different MSs participate in the provisioning of the requested E2E service. The path computation at this level is implemented as a domain selection according to the capabilities they offer, and the ones required by the service. The DT and the AI-decision MSs allow for a finer domain selection thanks to their enriched information and prediction capabilities. As for the technology domains, an E2E Resource Manager MS is dedicated to manage available resources from an E2E perspective over all domains, including multi-access network slicing capabilities, where an AI-based algorithm reserves and manages radio resources from cellular and Wi-Fi domains to maintain E2E QoS by enabling the steering of data across both accesses and meet the SLA of each slice. SLA requirements include maximum delay for low latency cases and minimum data rate for high throughput cases.

The E2E service automation MS orchestrates the provisioning process as well as the control loops associated to the maintenance of the service. Timely reactions to any anomaly (e.g., Key Performance Indicator (KPI) deviations) detected by monitoring the deterministic services are indeed crucial and, due to the complexity of the system, it would be unreasonable to rely on a human corrective intervention. Hence, automation is the most effective way to guarantee determinism at the E2E path. Given the hierarchical structure of the control plane and the number of MDs, multiple and concurrent CLs are possible. For that reason, Service Automation MSs, in each MFs, must provide CL governance (i.e., possibility configuring and monitoring the different stages of the loop) and coordination functionalities (i.e., conflict mitigation, race conditions avoiding, loop interactions) in line with the CL management operations and guidelines defined by ETSI ZSM. Finally, the time synchronization management MS is responsible for the inter-domain time synchronization by enabling a cross-technological domain time synchronization.

In addition to the aforementioned E2E MS, three specific Inter-Domain integration MS services are also defined. The MS registry is needed to register technology-specific and E2E MS, their management capabilities and the service access points. A Discovery MS is defined to query the registry for MSs with specific capabilities. Finally, a Recovery and High Availability MS is required to introduce mechanisms for monitoring the health and responsivity of the MSs and MDs, allowing to initiate self-recovery actions if needed.

3.3 Data Plane Abstraction

Domains are controlled by their respective MD, which integrate with domain technology-specific APIs and interfaces on their South-bound interface and provide technology agnostic services on their North-bound interface towards the E2E MD. The North-bound APIs implement: (1) the exposure of the domain's deterministic capabilities; (2) the exposure of control mechanisms through which the domain's data plane can be dynamically programmed; and (3) the collection of data plane measurements from the domain quantifying the state of the flows, resources, services, and the level of the achieved QoS. The combination of all the functionalities creates a domain abstraction that enables the E2E MD to integrate multiple domains regardless of their specific technologies into a coherent cross-domain deterministic service. These APIs are provided uniformly by each domain abstraction towards the E2E MD, assuming that the technology of the domain implements the necessary enablers.

The abstraction of a domain Is interpreted in the context of the domain's logical topology. The logical topology consists of: (1) service endpoints, which represent the domain's potential ingress and/or egress locations for deterministic traffic; and (2) logical paths between the service endpoints, which abstract the domain's detailed internal topology into simple inter-endpoint connections. Based on this, topology abstraction, attributes are attached to each logical path to describe deterministic capabilities, resources, measurements and the network state along the path. Deterministic capabilities may contain whether the domain's data plane is equipped with any of 802.1Qvb [23] type of scheduling, PAREO [24], or de-jittering mechanisms; but they also contain the intrinsic (minimum) latency or the lowest achievable jitter along a specific path so that the E2E MD can consider the selection or avoidance of specific domains or paths within a domain during the composition of an E2E service. For deterministic mechanisms, their control points are exposed, such as the ability to turn a specific data plane mechanisms on/off, or to provide configuration for them such as scheduler parameters and traffic classification rules. Measurements are provided not only on the aggregation level of the domain's logical paths, but also on the aggregation of flows that are part of the same E2E service. This enables the E2E MD to understand not only the achieved network performance per domain but also how the measured E2E service quality is impacted by each domain's data plane. This insight is the enabler for autonomous decisions and actions delivered either on the domain level (directly by the domain specific MD) or on the E2E level (by the E2E MD).

4 Conclusions

This work presents a hierarchical AI-based control plane architecture designed for the management of E2E deterministic services over an heterogenous data plane, encompassing different network technologies across different administrative domains. The proposed solution is a functional architecture relying on a service-centric approach to provide flexibility, scalability and modularity. The architecture relies on several pillars for enabling: (1) network predictability and intelligent decision making (AI and DT), (2) timely services and network status awareness (Monitoring), and (3) E2E service provisioning and intelligent decision enforcement (i.e., frictionless orchestration). Their joint action enables network automation through the concept of control CL. The proposed solution aims to complement the existing control planes of each technology by operating on top of them and interacting through existing standard interfaces where possible. This requires properly abstracting the data plane through specific models, disclosed by exposure services in order to provide a coherent and unified view,

which is exploited to seamlessly provision E2E services across different and heterogenous network technology domains.

ACKNOWLEDGMENTS

This work has been partially funded by the European Commission Horizon Europe SNS JU PREDICT-6G (GA 101095890) Project.

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