Demonstration of a Control Plane in Support of E2E Deterministic Service Provisioning over a Multi-domain Multi-technology 6G Network

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***Abstract*—The use cases associated to the emerging 6G technology demand a dynamic and adaptive network operation capable of addressing the specific requirements of heterogeneous data plane technologies. This demonstration presents the operation of a multi-domain multi-technology control plane architecture designed to provision end-to-end (E2E) connectivity with deterministic performance guarantees. Key innovations highlighted in the demonstration include homogenized configuration of diverse data plane technologies, advanced topology abstraction enabling Key Performance Indicator (KPI)-aware path computation, and the use of digital twin (DT)-based KPI estimation to support deterministic connectivity configuration. These capabilities collectively showcase a promising approach for managing the complexity and performance demands of future 6G networks.**

Keywords—Deterministic services, KPI, 6G networks, Multi-domain

I. OVERVIEW

Future 6G systems and networks will need to provide support to highly demanding use cases like ultra-reliable low latency communications (URLLC) and Industry 4.0. A wide set of the applications associated to these use cases, like extended reality (XR) or Industrial IoT (IIoT), require connectivity services with deterministic guarantees, such as latency and jitter. For this reason, network determinism [1] has been identified as one of the key features of the 6G network infrastructure. Network determinism imposes fixed or tightly bounded values to the KPIs associated to a connectivity service regardless of the status of the infrastructure or the dynamic evolution of the service itself. In this regard, there have been significant efforts on developing different data plane technologies to provide guaranteed transmission delays across network systems [2] [3].

However, due to the stringent connectivity requirements of the applications and the complex operation of the data plane infrastructure, a control and management entity is needed to guarantee the enforcement of the mentioned KPIs [4]. In this regard, the Software Defined Networking (SDN) paradigm, enhanced with additional functionalities provided by cutting edge technologies such as digital twinning [5] and Artificial Intelligence (AI), arises as a valid candidate to provide connectivity services with guaranteed KPI fulfilment. Targeting to address the challenges of deterministic networks in the 6G context, this demonstration showcases a control plane architecture for the provisioning of E2E deterministic connectivity services over a multi-domain scenario implementing different data plane technologies.

II. INNOVATION

This demonstration presents the operation of an AI-based control plane architecture (AICP) to provide E2E deterministic services with guaranteed KPI fulfilment over a multi-domain multi-technology data plane (MDP). In particular, three different data plane technologies have been used, namely wired Time-Sensitive Networking (TSN, [6]) Ethernet, 3GPP with extended TSN support and WiFi with TSN capabilities. Fig. 1 illustrates the AICP architecture that has been demonstrated. The AICP follows a service-oriented approach where a set of Management Services (MSs) have been defined to implement the control functionalities. In order to support multi-domain and multi-technology operation, the AICP has been designed in two levels, namely Local Management Domain (MD) and E2E MD. In this way, the local MDs are instantiated over the different technological domains (i.e., 3GPP, Ethernet and WiFi), and the E2E MD is instantiated on top of the local ones, as overreaching entities, to provide the mentioned multi-domain operation [7].

Starting from the bottom of the control architecture, the MSs that have been demonstrated at local MD level are the Resource Configurator (RC), the Path Computation Element (PCE) and the Service Automation (SA). The RC is

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responsible not only for the configuration of the underlying data plane during the provisioning phase, but also for the collection of data plane information that will be further used by the PCE, such as data plane capabilities, resource availability and domain topology. In order to provide homogenized configuration and data collection from the different technological domains, the RC instances rely on a common interface, which is used for the communication between the data plane infrastructure and the local MDs. Such interface has been designed and implemented as an Open API [8], and resides on top of each of the technological domains network infrastructure to expose a common Northbound interface (NBI) to the AICP for configuration and data collection. The information obtained by the RC is consumed by the PCE to compose the topology of the domain that will be used to compute the local paths associated to the requested services.

To enable a harmonized operation in the different instances of the local MDs, a common information model has been selected to be used by the installed MSs to realize their operation. In particular, aiming at deterministic services support, the gluing technology that has been adopted is DetNet [9], which is being defined in the framework of the Internet Engineering Task Force (IETF) to provide a control plane that supports deterministic connectivity services over multiple transport technologies. Hence, at local MD level, the RC translates the data plane infrastructure into a DetNet-based topology, which is used by the PCE to compute deterministic paths upon the request of the SA. The SA is the component that centralizes the service configuration process at the local MD, which, upon reception of a local service configuration, it interacts with the specific hardware at the data plane through the Open API to enforce the necessary configurations.

Laying on top of the local MDs, the E2E MD is in charge of the E2E deterministic service provisioning over the multi-domain network. The first MS involved in this process is the Service Ingestion (SI), which is the entry point for the clients or operators to request an E2E service. The SI analyses the request and composes the one that will be sent to the E2E SA, which, like in the local MD case, is in charge of controlling the E2E provisioning process. The request received by the E2E SA contains detailed information about the requirements (i.e., KPIs) posed by the service. For the computation of the connectivity associated to the requested service, the E2E SA relies on the E2E PCE, which performs several tasks. First of all, the E2E PCE is responsible for collecting abstracted topological information from the underlying technological domains, which is exposed by the PCEs of the corresponding local MDs. To provide an abstract view, which contains enough information to allow the E2E PCE for an E2E path computation that fulfils the deterministic requirements posed by the requested service, a slicing approach has been used. In such approach, the border nodes of each domain are announced by the local PCE along with a set of pre-computed paths between them (i.e., slices). The performance indicators of such slices, for example latency, are announced as well. Targeting standards compliance, the model used for the abstraction of the topology is based on a set of IETF specifications [10]. Once the abstract topologies of each local MD have been collected, and the E2E abstract topology has been composed, the second task the E2E PCE is responsible for is the selection of the domain sequence that the connectivity associated to a requested deterministic service will follow. More specifically, upon the reception of an E2E path request from the E2E SA, the E2E PCE uses the slice-based abstract topology to select the slices the service has to use to fulfil its connectivity requirements. The E2E PCE extracts the domain sequence from the computed abstract route, and contacts the SA of each local MD to request the provisioning of the path according to the characteristics offered by the announced slice. In this way, the E2E PCE is able to split the E2E deterministic service KPIs (e.g., the latency budget) among the involved technological domains.

It is worth noting at this point that, since the AICP has a flexible architecture based on microservices, additional components can be added to provide extended functionalities, for example based on AI. For instance, in the proposed demonstration, a DT MS has been installed in the E2E MD (as depicted in Fig. 1), which is contacted by the E2E PCE to assess that the concatenated local paths computed by the local MDs to support an E2E service fulfil the KPIs stated in the request. Similarly, the MD of the wired TSN domain hosts a DT aimed to check that the computed local path will not only satisfy the requirements of the request, but it will not affect the performance of the active ones either [11].

In light of the above, the main innovations provided by the proposed and demonstrated control plane can be summarized as follows:

- E2E control and management of deterministic connectivity is achieved thanks to the two-layer architectural design.
- The service-oriented approach allows for dynamic control architecture that can adapt to the heterogenous characteristics of the multiple data plane technologies. Moreover, extended functionalities can be added independently to the different MDs (e.g., IA, DTs).

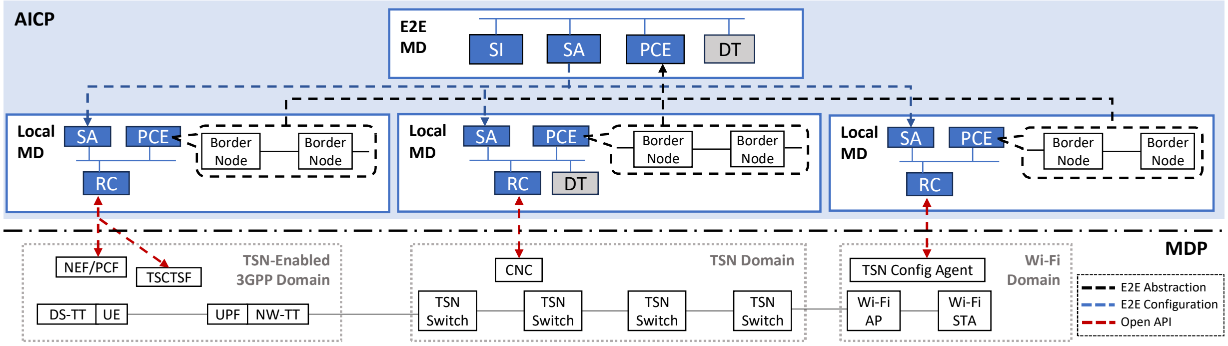

Fig. 1. Control Plane architecture and reference scenario.

- The use of an Open API allows for homogenized configuration and management of the different technological domains.
- The KPI-informed topological abstraction following the IETF approach allows for E2E path computation in support of deterministic services.

III. DEMO CONTENT AND IMPLEMENTATION

The main purpose of the proposed demonstration is to showcase the operation of the AICP architecture described in the previous section. In particular, the mentioned innovations related to the homogenized configuration of the heterogeneous data plane technologies and the E2E deterministic service provisioning, which relies on standards-compliant abstract view of the overall scenario, are demonstrated. To this end, the network scenario depicted in Fig. 1 has been used. The experimental set-up is located in the 5Tonic facilities in Leganés [12]. The MDP connects an Intel-based Wi-Fi TSN network (equipped with IEEE 802.1Qbv scheduling and over-the-air 802.1AS synchronization) with a wired TSN Domain, leveraging IEEE 802.1 TSN FRER, which is in turn connected to a 5G core provided by Ericsson. The AICP is hosted in two Dell PowerEdge R630 edge servers, each fitted with dual Intel Xeon E5-2620 v4 (2.10 GHz) processors and 128 GB of DDR4 RAM; all software modules are containerized and orchestrated with Kubernetes [13], while the underlying infrastructure is managed through OpenNebula Sunstone [14].

A. Topology Exposure and Abstraction

As said, one of the innovations showcased in this demonstration is the standards-based abstraction of the MDP topology. The collection and abstraction of the data plane topology and characteristics is implemented in two levels, and its workflow is depicted in Fig. 2. In the first level, the RC of the local MD collects the specific data plane information by means of the Open API introduced in section II (step 1 in the figure). Thanks to a common NBI, the RCs in charge of the multiple technological domains can collect this information in a homogenized way. In the second level, the PCEs of each local MD compose and expose an abstracted view of the technological domain they are responsible for (steps 2 and 3). The different portions of the local abstract topologies are used by the E2E PCE to compose the complete abstract view of the scenario. Since this demonstration is devoted to the AICP operation, we put the focus on this second level of abstraction, which follows a slicing approach that enables the KPI-aware E2E path computation.

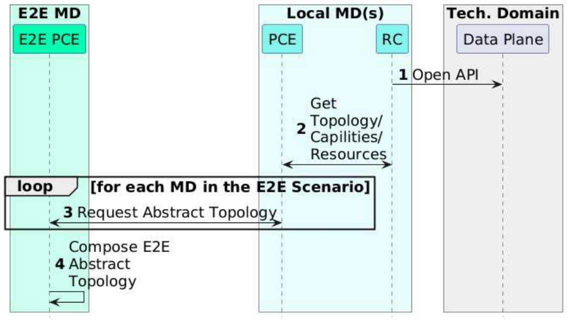

Fig. 2. Exposure workflow.

B. Provisioning workflow

Fig. 3 illustrates the main workflow that is showcased in this demonstration. As depicted, the provisioning process is started by the user (e.g. the operator), who requests an E2E service with a set of deterministic requirements (step 1). The request is received and processed by the E2E SI, which processes it to compose the fine-grained request that will be used by the E2E SA to request the path E2E PCE (step 3). The E2E PCE computes a domain sequence that, according to the abstract topology, is likely to fulfil the requirements conveyed in the request, and contacts such domains to request local path computation (step 5). The SA in charge of each local MD involved in the domain sequence receives the request from the E2E PCE and starts the local path computation process (steps 6 to 9). As highlighted in section II, the path computation process can be assisted by additional MSs (e.g., DTs) that can be installed at both local and E2E level. The E2E PCE collects the local paths and composes the E2E one (step 10). In this demonstration, the E2E MD implements a DT, which will provide an estimation of the KPIs that will be achieved by the computed path (step 11). If the estimation matches the requirements posed by the request, the path in sent back to the E2E SA for provisioning (steps 12 and 13). Finally, steps 14 to 18 illustrate the provisioning phase where the E2E SA contacts the local SAs to request the connectivity configuration. Such configuration is realized by the RCs by means of the Open API.

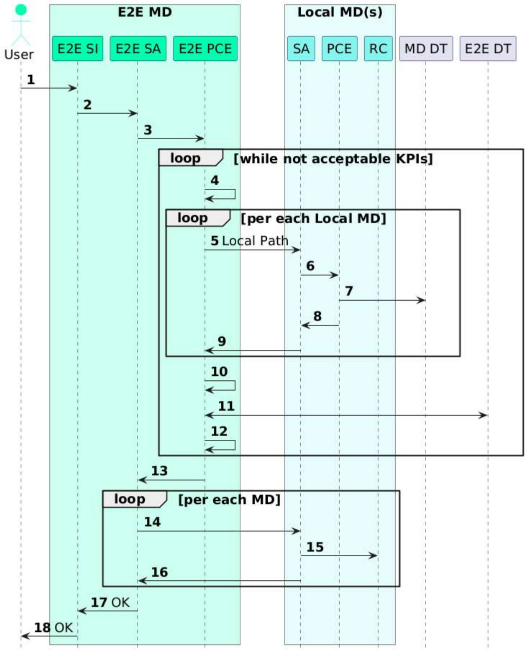

Fig. 3. Provisioning workflow.

C. Implementation and execution

Having presented the workflows that are demonstrated, this section focuses on the actual implementation and execution at the previously introduced experimental infrastructure. Fig. 4 illustrates the main steps of the execution, focusing on the interactions between logical elements, starting with the boot-up of the control plane. In particular, the PCE MSs of the different domains are started to showcase the collection of the data plane topology of the different technological domains. To achieve this, the PCE of each local MD interacts with the corresponding RC (Fig. 4 (a)). Once the local MD PCEs are up, running, have collected the specific data plane topology and composed their abstract views, the E2E PCE is started and contacts the PCE instances of the local MDs to collect the single-domain abstract topologies (Fig. 4 (b)). With this information, the E2E PCE composes the abstract topology of the complete E2E scenario. Then, the main part of the demonstration focuses on the provisioning phase. This process is started by sending an E2E deterministic service request to the E2E SI by means of its exposed REST interface. Such message triggers the provisioning process illustrated in Fig.4 (c), where the E2E SA sends the path request to the E2E PCE. Next, the E2E PCE computes the domain sequence and distributes the E2E latency among the domains according to the capabilities collected from each domain through the abstraction process. With this information, the E2E PCE requests the local path computation to the underlying SAs, which, in turn, forward the request to the corresponding PCEs. Once the E2E PCE has collected the local paths, it composes the complete E2E route and requests the DT for the KPI validation. If the estimated KPIs fulfil the requirements posed by the request, the path is sent to the E2E SA for provisioning. In this last phase, the E2E SA requests the provisioning to the SAs of the involved local MDs, which, in turn, request for the low-level configuration to their respective RCs. Finally, the RCs configure the multiple data plane infrastructures by means of the implemented Open API.

```
Source        Destination   Protocol   Info
10.5.15.65    10.5.100.25   HTTP       GET /topology_exposure HTTP/1.1
10.5.100.25   10.5.15.65    HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.61    10.5.100.21   HTTP       GET /topology_exposure HTTP/1.1
10.5.100.21   10.5.15.61    HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.66    10.5.15.67    HTTP/JSON  POST /Topology HTTP/1.1 , JSON (application/json)
10.5.15.67    10.5.15.66    HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.66    10.5.15.65    HTTP       GET /mdservice/topology HTTP/1.1
10.5.15.65    10.5.15.66    HTTP/JSON  HTTP/1.1 200  , JSON (application/json)
10.5.15.66    10.5.15.61    HTTP       GET /mdservice/topology HTTP/1.1
10.5.15.61    10.5.15.66    HTTP/JSON  HTTP/1.1 200  , JSON (application/json)
10.5.15.66    10.5.15.67    HTTP       GET /mdservice/topology HTTP/1.1
10.5.15.67    10.5.15.66    HTTP/JSON  HTTP/1.1 200  , JSON (application/json)
10.254.5.197   10.5.15.66     HTTP/JSON  POST /e2eservice/pathrequest HTTP/1.1 , JS
10.5.15.66     10.254.5.197   HTTP       HTTP/1.1 200   (text/plain)
10.5.15.66     10.5.15.61     HTTP/JSON  POST /path/mdservice/pathrequest HTTP/1.1 ,
10.5.15.61     10.5.15.66     HTTP/JSON  POST /mdservice/pathrequest HTTP/1.1 , JSO
10.5.15.66     10.5.15.61     HTTP       HTTP/1.1 200   (text/plain)
10.5.15.61     10.5.15.66     HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.66     10.5.15.61     HTTP/JSON  POST /path/mdservice/pathresponse HTTP/1.1
10.5.15.61     10.5.15.66     HTTP/JSON  POST /mdservice/pathcomputationresponse HT
10.5.15.66     10.5.15.67     HTTP/JSON  POST /path/mdservice/pathrequest HTTP/1.1 ,
10.5.15.67     10.5.15.66     HTTP/JSON  POST /mdservice/pathrequest HTTP/1.1 , JSO
10.5.15.66     10.5.15.67     HTTP       HTTP/1.1 200   (text/plain)
10.5.15.67     10.5.15.66     HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.66     10.5.15.67     HTTP/JSON  POST /path/mdservice/pathresponse HTTP/1.1
10.5.15.67     10.5.15.66     HTTP/JSON  POST /mdservice/pathcomputationresponse HT
10.5.15.66     10.5.15.65     HTTP/JSON  POST /path/mdservice/pathrequest HTTP/1.1 ,
10.5.15.65     10.5.15.66     HTTP/JSON  POST /mdservice/pathrequest HTTP/1.1 , JSO
10.5.15.66     10.5.15.65     HTTP       HTTP/1.1 200   (text/plain)
10.5.15.65     10.5.15.66     HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
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10.5.15.65     10.5.15.66     HTTP/JSON  POST /mdservice/pathcomputationresponse HT
10.5.15.66     10.5.15.67     HTTP/JSON  POST /E2E_KPIEvaluation HTTP/1.1 , JSON (a
10.5.15.67     10.5.15.66     HTTP/JSON  HTTP/1.1 200 OK , JSON (application/json)
10.5.15.66     10.254.5.197   HTTP       HTTP/1.1 200   (text/plain)
```

Fig. 4. Exposure and provisioning operation.

IV. Conclusions

The use cases that have been defined in the context of 6G networks require of dynamic operation tailored to the specific characteristics of the heterogeneous data plane technologies. In light of this, this demonstration has showcased the operation of a multi-domain multi-technology control plane architecture, which is able to provision E2E connectivity with deterministic characteristics. Several innovations have been demonstrated, such as homogenized data plane configuration, enhanced topology abstraction to enable KPI-aware path computation and DT-based KPI estimation in support of determinism.

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