Standardisation Assessment of a Digital Twin-Based Multi-Domain Deterministic Communications System

Sebastian Robitzsch*, Antonio de la Oliva†, Carla Fabiana Chiasserini‡, Claudio Ettore Casetti‡,
Fernando Agraz§, Giada Landi¶, Luis M. Contreras‖, Peter Szilagyi**, Pietro G. Giardina¶,
Rafael Rosales††, Salvatore Spadaro§, and Valerio Frascolla††
*InterDigital Europe Ltd, London, United Kingdom, Email: sebastian.robitzsch@interdigital.com
†Universidad Carlos III de Madrid, Leganés, Spain, Email: aoliva@it.uc3m.es
‡Politecnico di Torino, Turin, Italy, Email: {carla.chiasserini, claudio.casetti}@polito.it
§Universitat Politècnica de Catalunya, Barcelona, Spain, Email: {fernando.agraz, salvatore.spadaro}@upc.edu
¶Nextworks S.r.l., Pisa, Italy, Email: {g.landi, p.giardina}@nextworks.it
‖Telefonica, Madrid, Spain, Email: luismiguel.contrerasmurillo@telefonica.com
**Nokia Bell Labs, Budapest, Hungary, Email: peter.1.szilagyi@nokia-bell-labs.com
††Intel Germany GmbH, Munich, Germany, Email: {rafael.rosales, valerio.frascolla}@intel.com

***Abstract*—Many service flows between client and server endpoints traverse multiple computer networks even for a private network deployment. The challenge of reducing the complexity of such services is researched on by the European Commission-funded project PREDICT-6G, with special focus on deterministic communications. The provisioning of service flows over a multi-domain multi-technology group of computer networks is a particular challenge if each domain comes with its own set of deterministic communication support. To address that, an overarching End-to-End control plane is being developed in the project and is described herein. As the proposed innovations require a mix of technologies from Standardisation Development Organisations, this paper assesses the proposition of PREDICT-6G against the ongoing work in 3GPP, IETF, ETSI and IEEE.**

***Index Terms*—Standardisation, Time-Sensitive Networking, Deterministic Communications, Digital Twin, System Architecture**

I. Introduction

In the rapidly evolving landscape of telecommunication technology, it is of paramount importance to ensure seamless interaction between various system components developed by different vendors. The definition and specification of how components interact and function form the foundation of this interoperability. As the technology ecosystem becomes increasingly complex, the necessity for a set of global standards for telecommunication systems has become more pronounced. Such a standard offers a unified framework that enables interoperability across vendors and deployments.

The development and adoption of global standards have profound implications for the industry. By harmonising the technical specifications and operational protocols, the global standards facilitate compatibility and integration across diverse devices and networks from different vendors. This interoperability is critical for the deployment of cohesive, scalable, and efficient technological solutions. Customers benefit significantly from this uniformity, as it ensures that their services and end devices function reliably and consistently on a global scale, irrespective of the vendor or geographical location.

With respect to the development of technology for 6G, the International Telecommunication Union (ITU) released their International Mobile Telecommunication (IMT) 2030 vision in November 2023 [1], providing six usage scenarios and four overarching aspects each usage scenario shall address. Based on this recommendation, requirements are being developed within ITU so that Standardisation Development Organisations (SDOs) can then officially start drafting normative text on 6G technologies, with the aim to get technical proposals for 6G specifications back to ITU by early 2028. ITU will then assess and define which feature set will compose the first 6G specifications, the coveted global unified standard.

This paper explores the underlying principles and methodologies that drive the creation of a global standard for PREDICT-6G's multi-domain, multi-technology deterministic communications system. In order to provision service flows in an End-to-End (E2E) fashion, the ambition is to design an overarching control plane to abstract the domain specific control mechanisms from the E2E perspective, which can then operate uniformly in terms of service management. To foster interoperability, this paper aims at analysing the current SDO landscape to standardise such proposition.

The rest of the paper is structured as follows: Section II describes the proposition of PREDICT-6G to enable E2E multi-domain multi-technology deterministic communications, including separate data plane and control plane considerations. Section III assesses PREDICT-6G's proposition towards rel-

This work has been partially funded by the European Commission Horizon Europe SNS JU projects PREDICT-6G (GA 101095890) and 6G-SHINE (GA 101095738).

evant SDO. Section V draws the paper conclusions of the assessment and provides a brief outlook how to follow the on-going standardisation efforts by PREDICT-6G members.

II. The PREDICT-6G Proposition

This section presents the PREDICT-6G proposition on how to enable the service flow provisioning across different domains and data plane technologies in an E2E fashion. The content is organised around a high-level system blueprint composed of a Multi-Domain Data Plane (MDP) and an Artificial Intelligence (AI)-Driven Control Plane (AICP).

A. High-Level System Blueprint

PREDICT-6G defines three stringent characteristics for enabling deterministic communications, i.e., reliability, time sensitiveness, and predictability [2]. As described in further details in [3], to enable a time-sensitive packet delivery with a certain reliability and guaranteed upper/lower limits (predictability), it requires special considerations on the packet switching behaviour inside each domain on their data plane as well as advanced mechanisms on the control plane across domains to achieve that. The PREDICT-6G high-level system blueprint to enable such system is illustrated in Fig. 1 and entails:

- A user or application on the top that can request the provisioning or removal of service flows with specific Quality of Service (QoS) requirements around deterministic communications.
- E2E Management Function (MF) implementing Closed-Loop (CL) automations for the service flow management and a service repository to store stateful information.
- Domain-specific MF unifying the communication between the technology domains and the E2E MF, including exposure of capability and data monitoring, and service flow management.
- Domain-specific networks with their own control and user/data plane components.
- It is foreseen that a Digital Twin (DT) drives the CL automation with supporting domain-specific DT functional components in each domain-specific MF.

B. End-to-End AI-Driven Control Plane

The PREDICT-6G AICP is designed to enable the lifecycle management and control of E2E deterministic services across multiple networks, characterised by different technologies and variable support to determinism. To face such a challenging objective, the AICP design is modular and adaptable to the specificity of different network technologies. Each MF implements one or more of the so-called Management Services (MSs), which characterise the service-based architecture of the control plane that can be classified in three different groups:

1) Digital Twinning and AI solutions
2) Data collection and management
3) Frictionless orchestration and network control

The MSs in Group 1 are in charge of enabling smart resource allocation, i.e., AI-driven optimisation of network

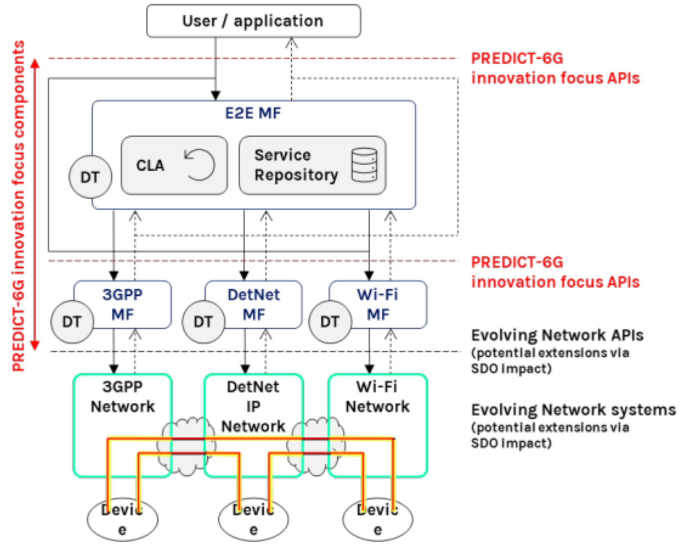

Fig. 1. PREDICT-6G High Level System Blueprint [4].

resource usage, prediction of service Key Performance Indicators (KPIs) in a sandbox environment, i.e., a DT of the target network environment, and data analysis, and decision for autonomous service assessment and tuning (see Section III-C4). Data collection and management MSs (Group 2) allow the pervasive and continuous monitoring of service and network parameters and KPIs, exposing them to the consumer, e.g., user, applications, other AICP functions in both near real-time, useful to trigger an immediate reaction to a given event, and in form of historical time series, useful for predicting service flow management actions and training AI models. Group 3 encompasses all the MSs devoted to the service orchestration and network provisioning and control. This includes exposure services for network resources, topology and capabilities, network programmability services, path computation, and deterministic service management.

One peculiarity of the AICP architecture is to be a 2-layer hierarchy, where the lower layer is a set of control platforms, each one insisting on a network characterised by specific deterministic technology, e.g., Time-Sensitive Networking (TSN). The environment where each control platform resides is called a Management Domain (MD), while the underlying network environment is called Technology Domain (TD), where the control platform can provision and control local deterministic services. At the upper layer, an E2E control platform provides cross-domain functionalities for the management and control of the E2E deterministic services, which are built as the stitching of the different deterministic local services created in each domain by the specific control platform at the local MD. Both local and E2E MDs manage and control deterministic services so the MSs belonging to the three groups are implemented for both layers: Path Computation Element (PCE) and E2E PCE, Service Manager and E2E Service Manager, and so on. Some MSs belonging to the local MD directly interact with the network at the TDs, via the interfaces offered by

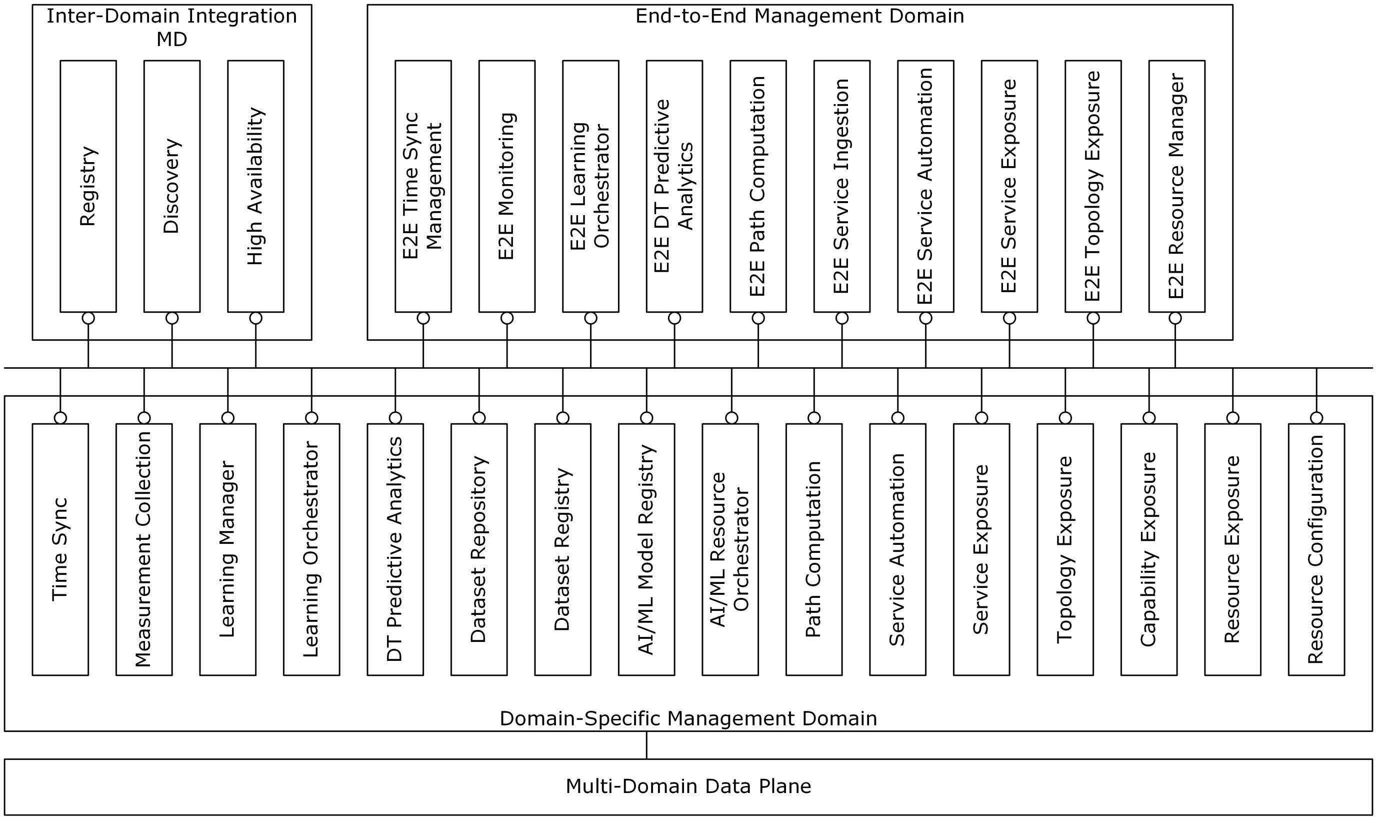

Fig. 2. PREDICT-6G AI-Driven Control Plane System Architecture [4].

the specific network technology properly augmented to fill the gaps in the network programmability, if any, while the interaction between local and E2E MDs happens via brand new interfaces. In particular, the MSs at local MDs offer to the E2E MS always the same normalized interface and information models, regardless of the underlying network technologies, allowing the E2E control platform to provision deterministic services in the different TDs, as they would be the in same network. Note that this technical proposition is of key interest to the PREDICT-6G project and a core ambition for writing this paper to assess its feasibility towards standardisation. A more comprehensive description of the AICP can be found in the public Deliverable 3.1 of PREDICT-6G [5].

C. *Deterministic Multi-Domain Data Plane*

In order to enable a time-sensitive and predictable packet delivery, special considerations on the packet switching behaviour inside the network components on the data plane is required. Key PREDICT-6G innovations for a deterministic data plane are described herein. The MDP foundation is the set of IEEE 802.1 specifications, referred to as TSN. [6] provides a comprehensive description of all MDP innovations.

1) Time-Sensitive Networking on Wi-Fi:

a) Scheduling - Target Wake Time: Achieving deterministic medium access is crucial to enhance support of time-sensitive applications, by avoiding long frame transmissions on the channel that contribute to increased worst-case latency. The IEEE 802.11 Target Wake Time (TWT) feature helps mitigate this by centralising channel access and can be leveraged to schedule data transmissions, giving priority to time-sensitive traffic. However, TWT alone does not guarantee a minimum Age of Information (AoI), since Wi-Fi frames could remain in the transmission queue longer than the maximum allowable AoI before being scheduled in a TWT window. Therefore, it is critical to adopt a scheduling strategy that accounts for buffer generation times and deadlines. This project will develop an extended digital twin based on the NS-3 simulator, which will model WiFi basic service sets and their connected stations, implementing the TWT mechanism and an algorithmic approach to optimally configure transmission windows for uplink traffic. In addition to ensuring deterministic access, energy consumption will be considered a key performance metric.

b) Redundancy: Another dimension to improve the wireless domain determinism is to exploit path diversity to address random channel problems. PREDICT-6G studies how multiple paths can be leveraged, e.g., via multiple radios or Multi-Link Operation (MLO) on a single radio, to reduce the latency distribution of packets, improve the roaming experience in mobility use cases, and increase the resilience to attacks [7].

2) Data Unit Groups for Time-Sensitive Networking: In scenarios where the number of arriving packets at a TSN switch peak above the maximum number of packets to be handled within a cycle, packet drops are the last resort. To avoid random dropping, the concept of Data Unit Groups

(DUGs) is designed as an extension to IPv4+6, allowing sending compute nodes to tag IP packets as a group that carries a single application data unit [8], thus intermediate switches can drop entire groups instead of random packets, possibly affecting more than one group.

III. Standardisation Assessment

This section assesses the proposed PREDICT-6G architecture against ongoing SDOs efforts. It is worth noting that when pointing at SDOs, both standardisation and pre-standardisation working and research groups, respectively, are considered. The intended outcome of this assessment is threefold:

1) Align: Identify the most suitable working and research groups in SDOs is key to exploit project results, following the EC code of practice on standardisation [9].
2) Identify Gaps: As part of the proposed PREDICT-6G architecture aligns with ongoing work in SDOs, one main proposition focuses on identifying gaps based on the research conducted.
3) Impact: If gaps are identified and arguments towards proposing an amendment are technically sound and feasible, contributions should be made to improve technical specifications, to enable the vision of a multi-domain multi-technology deterministic communication system.

A. Alignment to Standards

In order to assess PREDICT-6G's architecture with respect to possible alignment with SDOs, the proposed system blueprint and architectural details presented in Section II are put into a DetNet-centric high-level system blueprint drawing, as depicted in Fig. 3.

B. Multi-Domain Data Plane

This section describes the alignment of the data plane innovations presented in Section II-C to SDOs.

1) Deterministic Networking: To effectively integrate various technological domains into a unified E2E deterministic data plane, we leverage recent advancements from the Internet Engineering Task Force (IETF) DetNet working group. DetNet establishes deterministic data paths over Layer-2 bridged and Layer-3 routed segments, ensuring bounds on packet reordering, latency, loss, and jitter, and offering high reliability. By constructing a Layer-3 overlay data plane, DetNet exploits the deterministic properties of each technological domain.

The DetNet data plane architecture has two sub-layers: service and forwarding. The service sub-layer handles DetNet service protection and reordering, ensuring precise data packet handling. The forwarding sub-layer uses traffic engineering mechanisms to provide congestion protection, including low loss, assured latency, and minimized out-of-order delivery. The capabilities of each forwarding sub-layer may vary based on the technological segment.

End-systems connected to a DetNet domain encapsulate packets based on their service requirements. Edge DetNet nodes operate in both the service and forwarding sub-layers to deliver specified functionalities to incoming packets. Transit DetNet nodes, which might not be aware of DetNet service sub-layer requirements, provide essential QoS capabilities for traffic flows. The IETF DetNet architecture also envisions additional components like a control and management plane for configuring the data planes of DetNet nodes, ensuring per-flow QoS, and Operations, Administration, and Maintenance (OAM) mechanisms for maintaining deterministic properties [10].

The key point of this approach is to enable the DetNet data plane to interact with the specific TSN characteristics of each domain, i.e., configuring the queue discipline in IEEE 802.1Qbv or the Frame Replication and Elimination (FRER) using IEEE 802.1CB.

2) IP Header-Based Packet Data Unit (PDU) Sets: In Release 18, 3GPP introduced extensive support for extended reality applications allowing the 3GPP User Plane to serve different QoS flows within a PDU session, while ensuring the system is aware about their belonging to each other. For instance, an extended reality application is composed of a video, audio and haptics content which traverse the mobile network with different KPI requirements each. Using the knowledge about the three different QoS flows belonging to the same application, the mobile network can schedule the packet delivery on its User Plane across QoS flows of a single application. Part of this support of extended reality services is a feature called PDU Sets, which allows the mobile network to understand which packets belong together and carry a single application data unit, e.g., video frame. When resources are scarce, the network can start dropping individual PDU Set, knowing that video codecs for mobile devices can adapt and cope with individual frames not being received; it should be noted that 3GPP only enables PDU Sets for User Datagram Protocol (UDP)-based Realtime Transport Protocol (RTP) traffic. The concept of DUG presented in Section II-C2 enables the same logic, but for any IP-based traffic. Such feature is ideal for DetNet-based routers and TSN switches in particular to not only perform packet pre-emption and replication, but also to drop entire DUGs if there are too many packets to be processed within the set cycle time of a TSN switch. The aim is to bring the DUG concept as a new draft to the DetNet Working Group (WG) at IETF.

3) Wi-Fi Support for TWT: 802.11ax [11] already has comprehensive support for avoiding long frame transmissions and has specified a coordinate channel access referred to as TWT. These features allow the reduction of unexpected high latency peaks and allows prioritising time-sensitive in combination with 802.1Qbv [12]. However, Wi-Fi frames could remain in the transmission queue longer than the maximum allowable AoI before being scheduled in a TWT window. Therefore, it is critical to adopt a scheduling strategy that accounts for buffer generation times and deadlines, which will require further standardisation.

4) Wi-Fi Support for Path Diversity: Since 2017 the standard IEEE 802.1CB defines basic TSN redundancy capabilities, allowing to transmit information via multiple paths. This can be implemented till Wi-Fi 6 only via the use of

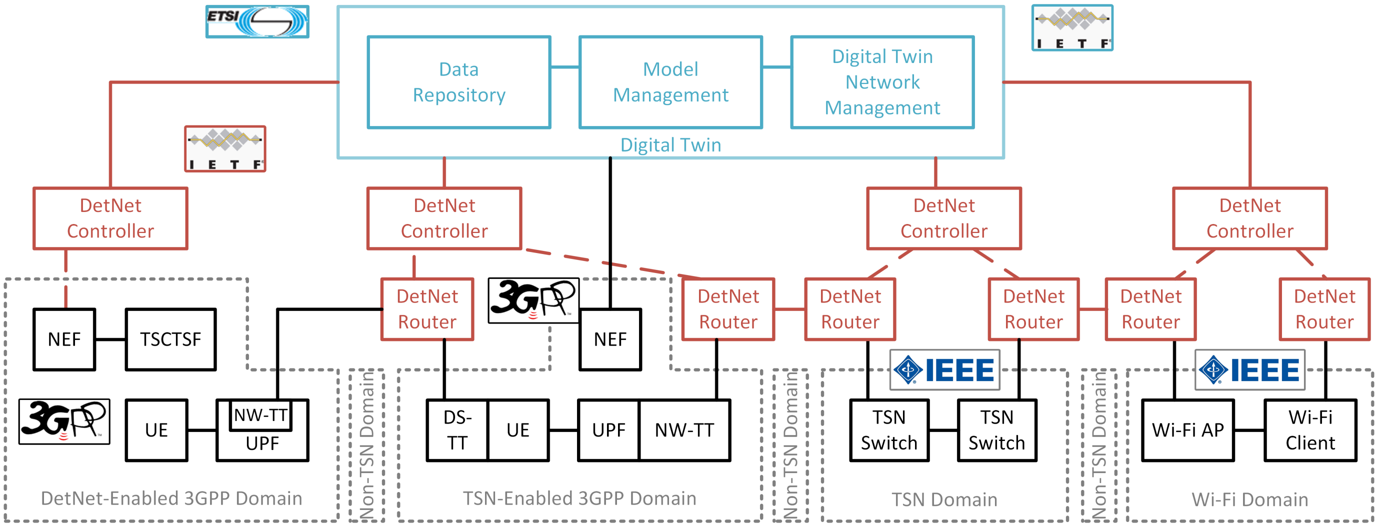

Fig. 3. Standardisation Development Organisation-Driven Holistic PREDICT-6G System Blueprint.

multiple radios and starting with Wi-Fi 7 via the MLO feature, which allows a single radio to connect simultaneously to multiple bands. Different operation modes of MLO have been defined to optimise latency or throughput [13]. Among them, Simultaneous Transmission and Reception (STR), where a single radio can send and receive packets at the same time, and extended Multi Link Single Radio (eMLSR), where a connection to different bands is simultaneous. However, only one transmission/reception operation can occur at any point in time, allowing to switch to a better band when necessary. The research in PREDICT-6G focuses on identifying improvements in the upcoming Wi-Fi 8 standard for enhanced determinism.

C. AI-Driven Control Plane

The AICP exploits several specifications from 3rd Generation Partnership Project (3GPP), IETF, Internet Research Task Force (IRTF) and European Telecommunications Standards Institute (ETSI) to model network topology and connectivity, abstracting the different technological domains as network nodes characterized by several ingress/egress endpoints that model the domain interconnection, as detailed in Section II-B.

1) Domain-Specific Control Plane Support: Since 3GPP Release 18, one can find support for both DetNet and TSN-enabled 3GPP networks in [14]. Both options essentially allow a 3GPP network to expose itself as a DetNet router or TSN switch with User Equipment (UE) and User Plane Functions (UPFs) as the ports of these routers/switches. Furthermore, 3GPP allows trusted Application Functions (AFs) to provide QoS requirements, traffic characteristic for QoS scheduling optimisation, and (most importantly for deterministic communications) time synchronisation.

2) Multi-Domain Topology Management: The ambition of PREDICT-6G is to handle the notion of determinism across multiple domains, not necessarily all deterministic. This implies the need of providing a certain degree of service guarantees (e.g., bounded latency or reliability) so that the E2E behavior can be considered deterministic.

As described, one of the basic assumptions in PREDICT-6G is the availability of data plane connectivity following the DetNet principles and encapsulation for data forwarding. This settles an initial building block on top of which form initial constrains and capabilities for service provision. Thus, an initial direction could consider DetNet as the baseline for the definition of control plane capabilities as well. This would include the definition of topology management in the system.

The topology management model as initially proposed in IETF DetNet [15] proposes the augmentation of the basic IETF topology model adding a number of attributes, such as:

- Bandwidth related attributes (e.g., bandwidth reserved for DetNet)
- Buffer/queue management related attributes (e.g., queue management parameters)
- Packet Replication, Elimination and Ordering Function (PREOF) capabilities and parameters (e.g., maximum out-of-order packets)
- Delay related attributes (e.g., node processing delay, queuing delay, link delay)

However, some other domains, such as Wi-Fi or 3GPP, do not have intrinsic support for such kind of attributes (or at least, not all of them), making it impossible to extend the same topology model approach for the E2E topological abstraction. There is a need for simplification or further abstraction of a DetNet domain, which would permit the provision of deterministic services flows.

With that in mind, the approach taken for the definition of an overarching multi-domain topology management model is based on network slicing, following the IETF efforts described in [16]. Such approach defines the network slice service as a set of connectivity constructs among Service Demarcation Points (SDPs) at the boundary of each domain. This is the key aspect to link this abstract level view with the deterministic expectation, since Service-Level Objectives (SLOs) could be defined in a manner that represents deterministic behavior. This can be translated towards the underlying technological domain to specific policies (i.e., DetNet features or guaranteed service boundaries otherwise). For that purpose it is possible to leverage the definition of precision metrics [17] which can be enforced by path computation [18].

3) Network Digital Twin: Since July 2020 the IRTF Network Management Research Group (RG) (NMRG) has an active draft on concepts and reference architecture of a Network Digital Twin (NDT) [19], which is in line with the design of the AICP and the functionality of the DT of the SDO-driven system blueprint (Fig. 3), i.e., a data repository to collect capabilities, topology and monitoring information, Machine Learning (ML) model management (training, storage, inference), and network management (service flow management). One DT-related proposition by PREDICT-6G is the need to design a federated NDT with domain-specific components of all three functional blocks illustrated in Fig. 3.

4) Close-Loop Automation: The Zero touch network and Service Management (ZSM) is an ETSI Industry Specification Group (ISG) that aims at providing solutions for enhancing the networks with large autonomous capabilities, i.e., self-configuration, self-monitoring, self-healing and self-optimization minimizing the human intervention, with a number of different specifications, which includes architecture, requirements, mechanisms for automation, and use cases. Among them, ETSI ZSM worked to specify the concept of CL as base mechanism for the network and service automation and related control and management functions, to enable the frictionless coexistence of multiple CLs at the same time on the same resources while allowing their dynamic provisioning and configuration.

ETSI ZSM defines a CL as an entity composed by four stages [20] i) monitoring, ii) analysis, iii) decision, and iv) execution, to enforce the decision on the underlying controlled system. Analysis and decision stages can be AI-driven, especially in the case of predictive control actions. In their maximum flexibility the CL stages are completely orchestratable, i.e., entities for which a complete lifecycle management and dynamic configurations are possible.

PREDICT-6G implements the four CL stages by exploiting specific configurations of AICP MSs. At the provisioning of a deterministic service, the Monitoring and Data collection MSs are configured for continuously collecting data and monitoring its KPIs (monitoring stage). The information collected are then ingested by the corresponding NDT, which analyses the data, predicts the evolution of the KPIs and can request the tuning of the deterministic service if needed to guarantee the target QoS (analysis and decision stages). Finally, MSs belonging to the frictionless orchestration and network control enforce the decision (execution stage). It is important to note that, given the architecture of the AICP, for each E2E deterministic service multiple CLs can co-exists, i.e., one E2E CL with one local CL exists per constituent service flow. This may create instability due the enforcement of conflict decisions over the same system. In this sense, ETSI ZSM defines a specific CL management function, in charge of managing such complex situations, called CL Coordination. The CL Coordination is in general a sophisticated element that can nevertheless be simplified in the AICP taking into account that for each E2E deterministic service, the conflict may happen only between the E2E CL and single local CLs: a simple solution, in this case, is to give the priority to one of the two.

IV. Standardisation Activities

The standardisation activities across all projects funded by the Smart Networks and Services Joint Undertaking (SNS JU) [21], such as PREDICT-6G, are shared quarterly with the 6G Smart Networks and Services Industry Association (6G-IA) Pre-Standardisation WG [22] and published on the internet by the coordination action 6GOPS [23]. Note, the SNS JU is governed by a range of bodies such as a governing board with selective members of the 6G-IA and the European Commission (EC) which tightly links the 6G-IA Pre-Standardisation WG to SNS JU-funded projects.

In the first year of the project, PREDICT-6G contributed to all SDOs mentioned in this paper based on the research conducted by the members of the consortium. The project managed to deliver 18 contributions with nine adopted contributions. As the project deliverable reporting on these exploitation activities and achievements is treated sensitive, no citation can be provided.

V. Conclusions

This paper presents PREDICT-6G's E2E service flow provisioning innovations across multiple domains and data plane technologies, utilising AI within an NDT. Then data and control plane propositions are assessed against ongoing (or completed) specification work across telecommunication-focused SDOs, such as 3GPP, IETF/IRTF, IEEE and ETSI. The outcome of the assessment is that the project proposition can impact and shape the work across SDOs, allowing vendors and operators (public and private network) to deploy such forward-looking solutions to enable E2E service flows with deterministic QoS requirements.

It shall be noted though that the range of technical specifications required from different SDOs is quite broad. In particular, the control plane heavily relies on pre-standardisation documents from ETSI and IRTF, leaving a question mark on the actual standardisation and inclusion for the first 6G technical specification release in 2028. However, the project will use the outcome of the assessment as an input to steer its efforts towards contributions to the identified (pre-)standard groups.

References

[1] "Recommendation itu-r m.2160-0; framework and overall objectives of the future development of imt for 2030 and beyond," International Telecommunications Union, November 2023. [Online]. Available: https://www.itu.int/rec/R-REC-M.2160-0-202311-I/en

[2] P. G. Giardina, P. Szilágyi, C. F. Chiasserini, J. L. Carcel, L. Velasco, S. Spadaro, F. Agraz, S. Robitzsch, R. Rosales, V. Frascolla, R. Doost-nejad, A. Calvillo, and G. Bernini, "A hierarchical ai-based control plane solution for multi-technology deterministic networks," in *Proc. of the 24th International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing*, ser. MobiHoc '23. ACM, 2023.

[3] P. Szilagyi, L. M. Contreras-Murillo, D. R. Menéndez, P. Giardina, and A. De la Oliva, "6g architecture for enabling predictable, reliable and deterministic networks: the predict6g case," in *2024 IEEE Wireless Communications and Networking Conference (WCNC)*, 2024.

[4] *D1.2 PREDICT-6G framework architecture and initial specification*, PREDICT-6G Consortium. Zenodo, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.10495821

[5] *D3.1 Release 1 of AI-driven inter-domain network control, management, and orchestration innovations*, PREDICT-6G Consortium. Zenodo, 2023. [Online]. Available: https://doi.org/10.5281/zenodo.8398433

[6] *D2.2 Implementation of selected release 1 PREDICT-6G MDP innovations*, PREDICT-6G Consortium. Zenodo, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.10623910

[7] S. Scanzio, M. Rosani, G. Formis, D. Cavalcanti, V. Frascolla, G. Marchetto, and G. Cena, "Multi-Link Operation and Wireless Digital Twin to Support Enhanced Roaming in Next-Gen Wi-Fi," in *2024 IEEE 20th International Conference on Factory Communication Systems (WFCS)*, 2024.

[8] S. Robitzsch, C. Sarachandra, M. Starsinic, and X. de Foy, "Formation and Assertion of Data Unit Groups in 3GPP Networks with TSN and PDU Set Support," in *2024 IEEE Wireless Communications and Networking Conference Record. WCNC 2024*, 2024.

[9] "Code of practice on standardisation in the european research area," European Commission, 2023. [Online]. Available: https://research-and-innovation.ec.europa.eu/document/download/8ffd888b-ba1b-4b60-bd54-2759d761c723_en

[10] "Deterministic networking working group," IETF. [Online]. Available: https://datatracker.ietf.org/wg/detnet/about/

[11] "Ieee standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 1: Enhancements for high-efficiency wlan," IEEE, 2021. [Online]. Available: https://standards.ieee.org/ieee/802.11ax/7180/

[12] "Standard for local and metropolitan area networks-media access control (mac) bridges and virtual bridged local area networks amendment: Enhancements for scheduled traffic," IEEE, 2015. [Online]. Available: https://standards.ieee.org/ieee/802.1Qbv/6068/

[13] G. Cena, S. Scanzio, D. Cavalcanti, and V. Frascolla, "Seamless Redundancy for High Reliability Wi-Fi," in *2023 IEEE 19th International Conference on Factory Communication Systems (WFCS)*, 2023.

[14] "Ts23.501; system architecture for the 5g system (5gs)," 3GPP, 2024. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/23501-i60.zip

[15] X. Geng, M. Chen, Z. Li, and R. Rahman, "Deterministic Networking (DetNet) Topology YANG Model," Internet Engineering Task Force, Internet-Draft draft-ietf-detnet-topology-yang-01, 2023, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/draft-ietf-detnet-topology-yang/01/

[16] A. Farrel, J. Drake, R. Rokui, S. Homma, K. Makhijani, L. M. Contreras, and J. Tantsura, "A Framework for Network Slices in Networks Built from IETF Technologies," RFC 9543, 2024. [Online]. Available: https://www.rfc-editor.org/info/rfc9543

[17] G. Mirsky, J. M. Halpern, X. Min, A. Clemm, J. Strassner, and J. François, "Precision Availability Metrics (PAMs) for Services Governed by Service Level Objectives (SLOs)," RFC 9544, Mar. 2024. [Online]. Available: https://www.rfc-editor.org/info/rfc9544

[18] L. M. Contreras, F. Agraz, S. Spadaro, and Q. Xiong, "Path Computation Based on Precision Availability Metrics," Internet Engineering Task Force, Internet-Draft draft-contreras-pce-pam-03, Jul. 2024, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/draft-contreras-pce-pam/03/

[19] C. Zhou, H. Yang, X. Duan, D. Lopez, A. Pastor, Q. Wu, M. Boucadair, and C. Jacquenet, "Network Digital Twin: Concepts and Reference Architecture," Internet Engineering Task Force, Internet-Draft draft-irtf-nmrg-network-digital-twin-arch-06, 2024, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/draft-irtf-nmrg-network-digital-twin-arch/06/

[20] "Gs 009-1 v1.1.1. zero-touch network and service management (zsm); closed-loop automation; enablers," ETSI GSZSM, Jun. 2021.

[21] "Smart networks and services joint undertaking," SNS JU. [Online]. Available: https://smart-networks.europa.eu

[22] "Pre-standardisation working group," 6G Industry Association (6G-IA), 2024. [Online]. Available: https://6g-ia.eu/6g-ia-working-groups/#pre-standardization

[23] "Sns ju pre-standardisation tracker," 6GOPS, 2024. [Online]. Available: https://verticals-tracker.sns-ju.eu/standards-tracker/pre-standardisation