6G Architecture for Enabling Predictable, Reliable and Deterministic Networks: the PREDICT6G Case

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***Abstract*—The PREDICT-6G framework, a novel 6G network architecture aiming to provide reliable, predictable, and time sensitive networking across diverse applications, integrates a multi-technology, multi-domain network infrastructure, creating a homogeneous and deterministic E2E connectivity across wired and wireless elements. This architecture addresses the evolving needs of specialized applications, setting a new standard for future networking technologies. A key component is the AI-driven Multi-stakeholder Inter-domain Control-Plane, which ensures the seamless delivery of time-sensitive services.**

***Index Terms*—6G, Deterministic Networks, Multi-Technology Integration, Multi-Domain Infrastructure AI-Driven Inter-domain Control-Plane (AICP), TSN.**

I. Introduction

6G aims to build upon the advancements made by 5G, addressing the diverse and evolving requirements of various specialized applications. This involves significant improvements over 5G's current capabilities, particularly in bandwidth, latency, reliability, security, and energy efficiency. The goal of PREDICT-6G is to create a comprehensive 6G solution End to End (E2E), encompassing both architecture and protocols, to ensure the uninterrupted delivery of services for specialized applications with strict demands for timing and reliability. The project will focus on creating a Multi-technology Multi-domain network infrastructure that is deterministic in nature, encompassing both wired and wireless components and their interconnections. To encompass this, PREDICT-6G native multi-domain strategy involves the development of an AI-driven Multi-stakeholder Inter-domain Control-Plane (AICP), specifically designed to manage deterministic network paths, catering to time-sensitive services as per the demands of end-users, ranging from small-scale networks like those in a single vehicle to extensive, widely distributed networks. It is as well crucial to deploy a user-plane that effectively manages the complexities of multi-domain operations. This specialized user-plane is commonly referred to as the Multi-Domain Data Plane (MDP). The MDP plays a central role in ensuring seamless communication and data transfer across various domains within the network architecture

In this project, we understand determinism as "the union of reliable, time sensitiveness and predictable features". Time sensitive and predictability has well-known definitions but when we discuss reliability, the different definitions and understanding appears and not only with this concept.

A. Reliability

In 6G networks, reliability is crucial for consistent performance and uninterrupted service, as well as being a key aspect to ensure determinism across the network. This involves robust protection and replication mechanisms to counteract failures and maintain network integrity, such as Packet Replication Elimination Ordering Functions (PREOF) in IETF Deterministic Networking (DetNet) [1] or IEEE 802.1CB [2] Frame Replication and Elimination for Reliability (FRER). These strategies include redundancy, and fault tolerance, ensuring the network functions even with component malfunctions. Advanced error correction and resilient routing protocols further boost this reliability, enabling seamless data delivery even under stress.

B. Time Sensitiveness

Time sensitiveness refers to the ability to provide reliable and timely data transfer between communicating endpoints. This is particularly important when dealing with endpoints that may belong to different technological or administrative domains, as per the multi-domain principle.

Key technologies enabling this are DetNet and Time-Sensitive Networking (TSN) features over wired and wireless networks. DetNet ensures guaranteed data delivery with minimal latency as a layer that allows us to coordinate multiple domains under the same deterministic umbrella, while TSN focuses on precise timing for data transfers within each domain. These technologies are essential for applications requiring strict timing, such as industry 4.0 or autonomous vehicles.

C. Predictability

Predictability in 6G networks is essential for ensuring consistent performance and optimal user experience. In PREDICT-6G, this is achieved through the AICP and Digital Twin (DT). AICP algorithms will analyze network data to predict loads and potential failures, enabling proactive management of deterministic networks. Digital Twins, as virtual replicas of the network, allow for real-time simulation of certain services or configurations as well as problem-solving and anticipation. Together, these technologies enhance predictability by allowing network operators to foresee and mitigate issues before they impact network performance.

The paper is structured as follows: Section II delves into the system architecture principles of the PREDICT-6G framework, detailing its core components and operational paradigms. Section III presents the PREDICT-6G architecture, offering insights into its reference architecture and key elements. In Section IV, the focus shifts to multi-domain aspects within the PREDICT-6G framework, discussing the integration and management of various technology domains. Section V explores the management services critical to the PREDICT-6G framework, highlighting their roles and functionalities. The paper concludes in Section VI, where we discuss the seamless transition from 5G to 6G and its implications for the PREDICT-6G framework. Finally, conclusions and acknowledgments are provided in the last sections.

II. SYSTEM ARCHITECTURE PRINCIPLES

The aim of PREDICT-6G is to provide technology enablers and management automation for multi-domain end-to-end deterministic services. In this context, domains may mean both technological domains (i.e., network segments implemented with different communication technologies such as 3GPP, IP, TSN, Wi-Fi, etc.) and administrative domains (i.e., domains that are governed by separate entities, although they may or may not be realized with the same network technology).

This section introduces a set of architecture principles applicable to the PREDICT-6G system's reference architecture:

- **Principle 1: E2E deterministic services**
  The PREDICT-6G system enables E2E deterministic services between devices that may implement different network technologies or connect to different administrative network domains [3]. Therefore, E2E in PREDICT-6G context means multi-domain services. Deterministic E2E services mean E2E services with a given level of determinism, which are defined and measured by a set of quality-of-service characteristics already identified in [4]
- **Principle 2: Multi-domain service composition and management automation**
  The PREDICT-6G system builds E2E deterministic services by using capabilities and services of the constituent technology or administrative domains. This turns PREDICT-6G into a system that is deployed over existing network segments, and thus PREDICT-6G integrates with APIs defined by various technology domains and standards in order to realize the E2E service goals.
- **Principle 3: Modularity**
  The PREDICT-6G system consists of a set of loosely coupled, logically separated, self-contained services and functionalities (components in general), which are integrated through well-defined interfaces. Modularity enables any PREDICT-6G system implementation to use preferred technologies and mechanisms if the services provided by the system components conform to the PREDICT-6G interface specifications.
- **Principle 4: Extensibility to multiple / new technologies**
  The PREDICT-6G system provides E2E deterministic services over a set of heterogeneous technologies. These technologies are constantly evolving, and new ones might appear, which could be used to create E2E deterministic services. Extensibility enables the transfer of PREDICT-6G system capabilities and service to any new (or updated) technology.
- **Principle 5: Scalability**
  Scalability ensures that PREDICT-6G deployments can be adapted to the specific technology mix, topology, size, device, and network capabilities of the actual domains that become part of (coordinated by) the PREDICT-6G system.
- **Principle 6: Model-driven open interfaces**
  The PREDICT-6G architecture should define uniform information models both for the interaction between PREDICT-6G system components and for interacting with different technology domains for E2E service composition and assurance. The interaction between the consumer of the PREDICT-6G system should not depend on the technology domains, their technology specific APIs and capabilities.

III. PREDICT-6G ARCHITECTURE

This section provides the reference architecture of the PREDICT-6G system. The high-level architecture of PREDICT-6G is depicted in Figure 1, showing the various components of the two main architectural concerns: the management- and control-plane of PREDICT-6G, referred to as the AI-driven multi-stakeholder inter-domain control plane (AICP), and the user-plane of PREDICT-6G, referred to as the multi-domain data plane (MDP). The figure also indicates novel architectural components as well as integration with existing state-of-the-art technologies.

In PREDICT-6G, the MDP encapsulates both user-plane (U-plane) and control-plane (C-plane) technologies by various standard definition organizations. Therefore, MDP is a "smart user-plane" that provides packet/flow level data plane mechanisms that are programmable via their respective control-plane mechanisms. PREDICT-6G's AICP builds on these programmable data plane enablers to compose E2E cross-domain deterministic services, by orchestrating the mechanisms of the various underlying technology domains.

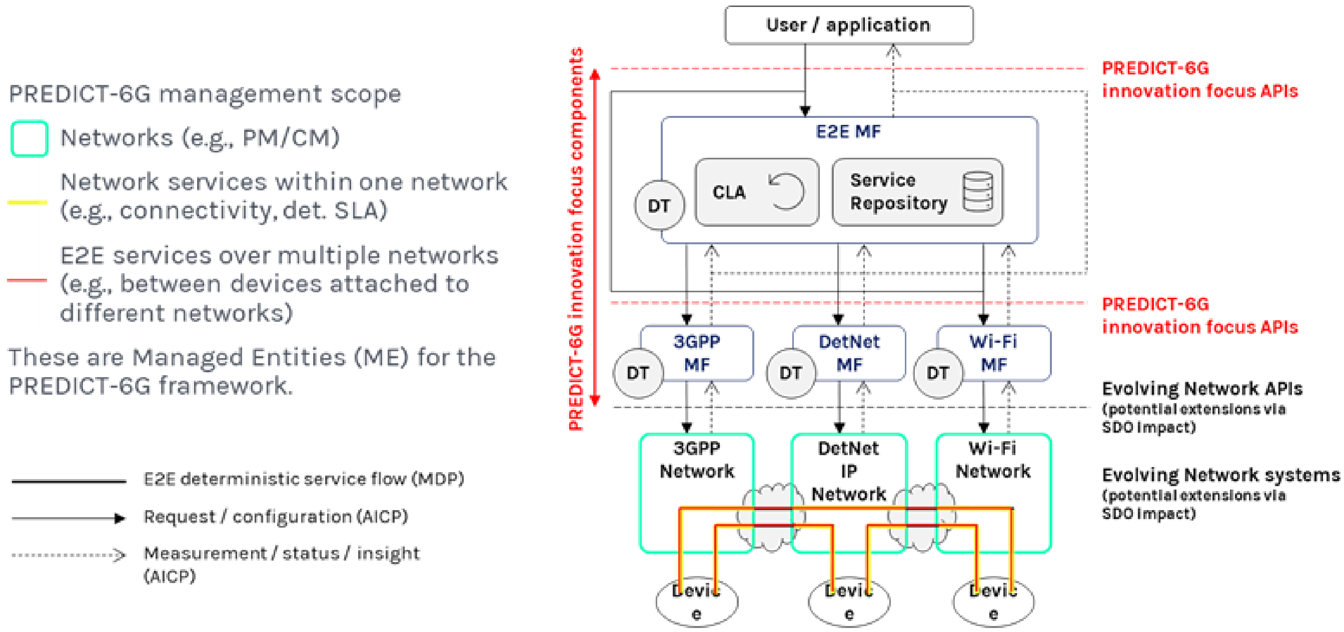

Fig. 1. The overall PREDICT-6G system architecture.

The AI-driven multi-stakeholder inter-domain control plane (AICP) of the PREDICT-6G system architecture collects capabilities that control and manage the data plane services in order to create and assure deterministic E2E service for simultaneous data flows with different quality-of-service characteristics. The AICP follows a service-based architecture design, where management capabilities are separated into Management Services (MS), which are further organized into Management Domains. MS are interworking via APIs defined individually per each Management Service.

In the PREDICT-6G AICP reference architecture, each Management Service provides its own API that may be consumed by any other MS. That is, the API of a MS is not specific to its consumer, which enables separation of concerns and implementations related to management capabilities.

IV. Multi-Domain Operation

Within the PREDICT-6G framework, the goal is to operate within a multi-domain scenario, and achieving this objective necessitates the integration of management services across diverse technology domains like IETF DetNet, 3GPP, and IEEE. This integration follows the architecture set forth by PREDICT-6G. For instance, in the IETF DetNet domain, services like Path Computation and Topology Exposure are pivotal for optimizing data routing and ensuring adherence to internet standards and protocols, allowing DetNet to deploy smoothly. In the context of 3GPP communications, services such as Resource Configuration, Service Automation, and Time Sync become crucial. They enable dynamic network adjustments and efficient management of 5G/6G network slices, as well as the distribution of a time reference to allow TSN features on the network. In the IEEE domain, focusing on time-sensitive networking, once again Time Synchronization, as well as Measurement Collection and Resource Exposure are decisive. These services guarantee the precise timing and reliability required by the IEEE 802.1 TSN standards to perform. Each management service within PREDICT-6G is tailored to enhance and support the specific requirements of these diverse technology domains, ensuring a robust, adaptable, and efficient network infrastructure.

The overarching design goal of PREDICT-6G is to enable deterministic E2E services over multiple technologies through a fully automated life-cycle management and quality assurance [4]. In this context, the figure attached (see Figure 3) illustrates the multi-domain approach of PREDICT's 6G architecture, showcasing the interconnectivity and interaction of various domain-specific management services and entities. This visual representation underscores the seamless integration and coordination across different network technologies, which is critical for the realization of smart manufacturing, critical communications, and multi-domain deterministic communication. Multiple technologies are meant to be different networking stacks, protocols, control- and user-plane mechanisms, that are defined and governed by their own standards. Prominent technologies within the scope of PREDICT-6G are 3GPP [5], IETF DetNet [6], IEEE 802.1 TSN and Wi-Fi [7]. The PREDICT-6G system enables devices connected to network segments implemented through these various technologies to connect to each other via deterministic services, to enable use cases such as smart manufacturing, critical communications, or multi-domain deterministic communication [4].

In the PREDICT-6G AICP architecture, a Management Domain (MD) is a set of interworking (federated) MS with the same scope (e.g., operating over the same group or type of managed entities).

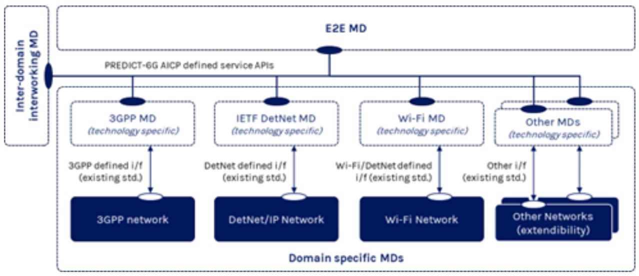

Fig. 2. Management Domains of the PREDICT-6G AICP architecture.

Management Functions (MF) are entities that may be used in combination with the MS to scope functional blocks in the AICP architecture. Logically, a MF is an aggregation of one or more MS, usually from the same Management Domain. The MF could be regarded as a single functional unit that provides functionality using the union of all services that its constituent MS offer. Implementation-wise, a MF may be a deployable software unit suitable for orchestration on a cloud infrastructure.

The PREDICT-6G AICP framework is structured around a two-layered architecture consisting of MDs and MSs, with the foundational layer being the Management Domains. These domains provide the overarching structure within which specific management functions are performed.

1) **Domain specific MDs**
   Scope: provide management services (CM/PM/service/SLA) for a given network technology (or administrative domain implemented by a given network technology), as illustrated in Figure 2. MSs in a domain specific MDs may interact with Managed Entities (ME)s in the underlying technology via ME-specific interfaces (e.g., 3GPP NEF); with other MSs in the same MS; and with MSs in the E2E MS via the service-based architecture.

   NOTE 1: implementation-wise, there are as many instances of domain specific MDs as the number of network technologies to be integrated under the PREDICT-6G system architecture. Currently, PREDICT-6G is targeting integration with 3GPP and IETF DetNet.

   NOTE 2: Despite the plurality of underlying network technologies, the service APIs of all domain specific MSs should be technology-agnostic, in order to enable scaling of the PREDICT-6G system architecture over other network technologies. Any technology specific aspect of a MS within domain specific MDs is contained within the integration of the MS with its respective ME(s).

2) **End-to-end (E2E) MS**
   Scope: provide management services for creating and managing end-to-end deterministic services over multiple networks with potentially multiple technologies. MSs in this MS interact with other MSs in the E2E MS and MSs in all technology specific MDs via the service-based architecture.

   NOTE 1: There is a single E2E MS in the PREDICT-6G system architecture.

3) **Inter-Domain Integration MS**
   Scope: MSs in this MS provide services for the PREDICT-6G framework itself (e.g., MS discovery and registration, high availability, resiliency, etc.). MSs in this domain interact with all other MSs in all MDs.

   NOTE 1: There is a single Inter-Domain Integration MS in the PREDICT-6G system architecture.

MS are responsible for providing diverse capabilities, such as configuration, data management, performance measurement, and analytics, each tailored to specific network needs. Below is a brief description of the key management services of each Domain Specific MS within the PREDICT-6G framework:

- **Time Synchronization:** Ensures that all network components are synchronized in time. This is crucial for maintaining the determinism.
- **Measurement Collection:** Involves gathering data on various network parameters like latency, throughput, and packet loss. This data is essential for monitoring network performance and making informed decisions.
- **Path Computation:** Determines the most efficient data paths across the network. Key for optimizing network resources and ensuring reliable data delivery within specified time constraints.
- **Service Automation:** Focuses on automating the deployment, scaling, and management of network services. This reduces manual intervention and increases the network's adaptability and responsiveness to changing conditions or requirements.
- **Service Exposure:** Involves making network services available to external systems and applications.
- **Topology Exposure:** Deals with providing a view of the network's structure. It allows for better planning and optimization of network resources.
- **Capability Exposure:** Involves exposing the network's capabilities, such as bandwidth availability and supported technologies. This is essential for efficient resource allocation and service provisioning.
- **Resource Exposure:** Makes information about network resources like routers, switches, and links available for management and optimization purposes
- **Resource Configuration:** Allows setting up and adjusting network resources to meet the requirements of different services. This includes configuring nodes to optimize performance and ensure service determinism.
- **Learning Manager:** Interacts with the AI/ML Resource

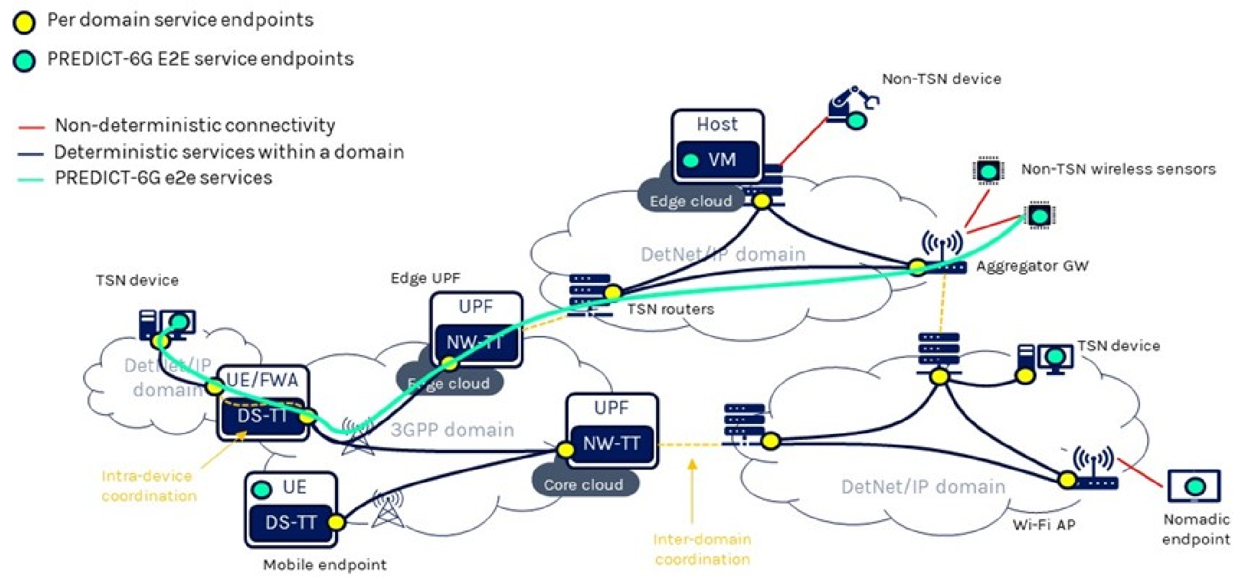

Fig. 3. Multi-domain approach of PREDICT's 6G.

Orchestrator, as well as with the AI/ML Model and Dataset Repositories and Registries, in order to retrieve an AI/ML model/dataset whenever needed.

- **Learning Orchestrator:** Coordinates the process of training AI/ML Models locally within a domain.
- **DT Predictive Analytics:** Predicts the KPIs of new and already established traffic flows (TSN, Best effort, etc) within a specific domain.
- **Dataset Repository:** Stores the datasets to be used for such AI/ML operations as model training.
- **Dataset Registry:** Includes the characteristics of datasets (e.g., size, domain, input features, privacy requirements, data statistics information).
- **AI/ML Model Registry:** Records the AI/ML model characteristics, e.g., structure, format of required input and provided output, complexity level, possible dataset that have been used for training (if any), last training/update operation (if any).
- **AI/ML Resource Orchestrator:** Operates locally within each domain, orchestrating computational and networking resources within the corresponding domain.

Management automation means to provide technological components that orchestrate the process of provisioning and configuring end-to-end deterministic services, and to take proactive / predictive actions during the lifetime of the services to ensure that the end-to-end deterministic targets are continuously met.

A MS provides one or more management capabilities (configuration, data, measurement, performance, analytics, control, etc.) with a scope (e.g., to control one or more MEs, or to provide services to other MSs). For example, an MS may provide deterministic service provisioning capability for a 3GPP network; or an MS may provide performance measurement services over an IETF DetNet network (which is then consumed by an analytics MS that evaluates the service quality). From the AICP point of view, a ME is an architectural component of the PREDICT-6G MDP.

V. Extension to non-deterministic domains

Network technologies with no native support for deterministic user plane mechanisms require extensions to make them capable of participating in the service of deterministic traffic. The extensions may be incorporated in two (non-exclusive, complementary) options:

- **Option 1:** Incorporate extended functionality into existing entities (e.g., end devices, intermediate nodes, software defined functions) that are already part of the non-deterministic domain's architecture.
- **Option 2:** Provide extended functionality in separate architectural entities (e.g., new nodes deployed in the U-plane).

VI. SEAMLESS TRANSITION FROM 5G TO 6G

5G has marked a significant leap in wireless communication with its high-speed, low latency, and increased capacity. However, as technology evolves rapidly, 5G's limitations are becoming more apparent. The transition to 6G is driven by emerging demands and technological advancements that 5G can't fully address. The progression from 5G to 6G within the PREDICT6G framework can be summarized as follows:

- Reliable to Ultra-Reliable Communications: 6G elevates reliability to ultra-reliable levels, critical for applications like remote surgery and autonomous transportation.
- Enhanced Data Rate and Capacity: 6G accommodates the exponential growth in data traffic and data-intensive applications.

- Predictive Network Management: 6G adopts proactive, AI-driven network management for real-time analytics and decision-making.
- End-to-End Deterministic Services: 6G ensures consistent service quality across applications with deterministic network behavior.
- Multi-Domain Service Composition: 6G seamlessly integrates and manages diverse network elements and services across domains.
- Low Latency for Time-Sensitive Applications: 6G meets stringent latency requirements for time-sensitive applications.
- Modularity and Extensibility: 6G enhances extensibility to incorporate emerging technologies while maintaining flexibility.
- Model-Driven Open Interfaces: 6G introduces open, model-driven interfaces for greater interoperability and customization.

VII. CONCLUSIONS

The PREDICT-6G architecture has two major components: the MDP and the AICP.

The MDP provides capabilities that enable to realize deterministic services within specific technology domains in a way that enables cross-domain integration in terms of time synchronization, distributed PAREO or PREOF type of mechanisms, improved reliability at domain borders. MDP also discusses architecture components that enable improving the level of determinism in network segments realized by technologies that have no built-in support for determinism.

The AICP defines management services that enable automated programming and configuration of the MDP capabilities. The AICP follows a service-based architecture, organized into two hierarchical layers: E2E and domain level. The E2E management services are collectively responsible to receive, provision and manage end-to-end deterministic services, including the assurance of their SLA during their lifetime. The E2E Management Services are technology-agnostic. Their role is to (1) receive and validate requests for E2E deterministic services; (2) split the E2E deterministic service requirements into per-domain targets, depending on the available domains, their capabilities and state; (3) delegate the responsibility of fulfilling per-domain targets to each domain's own Management Services; (4) handle conflicts or dynamic events that require re-balancing per-between targets. The E2E Management Services leverage the capabilities of Management Services defined at each technology domain.

The technology domain specific Management Services expose the same API towards the E2E Management Domains, but internally implement interfaces and mechanisms specific to their underlying network technology (e.g., devices, controllers) to fulfil the per-domain targets by means of the domain's own mechanisms and capabilities. This separation of concerns between E2E vs. technology specific realization of deterministic sub-goals makes PREDICT-6G extendible and scalable onto any number of different networking technologies and domains, providing a solid architectural foundation for creating multi-domain deterministic networks

ACKNOWLEDGMENT

This work has been partially funded by the European Commission Horizon Europe SNS JU PREDICT-6G (GA 101095890) Project, and the Spanish Ministry of Economic Affairs and Digital Transformation and the European Union-NextGenerationEU through the UNICO 5G I+D 6G-EDGEDT.

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