UNICO I+D Project
6G-DATADRIVEN-04

6G-DATADRIVEN-04-E7

Revised system architecture

Abstract

This report describes the revised system architecture to achieve reliable and deterministic network connectivity in Industry 4.0 environments. The revised system architecture focusses on the multi-technology connectivity layer that is split into multi-domain control plane and multi-domain data plain that will focus on ensuring the E2E service determinism in Industrial environments over multiple technologies. In addition, the role of Digital Twins in each of the technological domains is envisioned to provide predictability.

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List of Acronyms

3GPP: 3rd Generation Partnership Project (3GPP)

AI/ML: Artificial Intelligence / Machine Learning

DetNet: Deterministic Networking

DT: Digital Twin

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IoT: Internet of Things

MIMO: Multiple Input Multiple Output

NFV: Network Function Virtualization

RAW: Reliable and Available Wireless

SDO: Standards Developing Organization

URLLC: Ultra-Reliable Low Latency Communications

MCP: Multi-SDO Control Plane

MDP: Multi-SDO Data Plane

E2E: End to End

MS: Management Services

MD: Management Domains

ME: Management Element

DB: Data Base

TSN: Time Sensitive Networking

QoS: Quality of Service

KPI: Key Performance Indicators

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Resumen Ejecutivo

Este documento proporciona una version revisada del diseño inicial del sistema para el proyecto 6G-DATADRIVEN-04. El documento detalla las componentes de dicho sistema, y explica las extensiones necesarias para su puesta en marcha.

Los principales resultados descritos en este entregable son:

- la propuesta de una extensión del diseño inicial del sistema que proporcione información detallada para los componentes involucrados en la conectividad en escenarios de Industria 4.0;
- la propuesta de un plano de control multi-SDO que pueda ofrecer servicios deterministas E2E en escenarios de Industria 4.0;
- la propuesta de un plano de datos multi-SDO capaz de ejecutar las configuraciones proporcionadas desde el plano de control multi-SDO para garantizar una baja latencia, una alta confiabilidad y una alta disponibilidad, características necesarias en escenarios multitecnología de Industria 4.0; y
- la ampliación del concepto de gemelo digital (*Digital Twin*) en 6G-DATADRIVEN-04 para incluir análisis predictivos en la capa de conectividad.

En línea con la arquitectura propuesta en el presente documento, se ha llevado a cabo investigación relacionada con la industria conectada usando inteligencia artificial. En concreto, se ha publicado:

- una solución para reducir el número de estaciones activas con el fin de reducir la contención en el canal y ahorrar energía (Carlos Barroso-Fernández, 2023); y
- Los desafíos futuros para el uso de RAW como plano de control para redes deterministas inalámbricas (Bernardos, 2023).

El resto del documento está redactado en inglés, de cara a maximizar el impacto del trabajo realizado en este proyecto.

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Executive Summary

This document provides an revised version of the system design for 6G-DATADRIVEN-04. The document details the revised components of the system, and explains the required extensions.

The main contributions of this deliverable are:

- the proposal of an extension of the initial system design providing detailed information for the design components of the connectivity layer in Industry 4.0 scenarios;
- the proposal of multi-SDO Control Plane that can offer E2E deterministic services in Industry 4.0 scenarios;
- the proposal of multi-SDO Data Plane that executes the configurations provided from the multi-SDO Control Plane in order to guarantee the needed low-latency, reliability and availability in multi-technology Industry 4.0 scenarios
- the extension of the Digital Twin concept in 6G-DATADRIVEN-04 to include predictive analytics in the connectivity layer.

Inline with the proposed framework, the following research has been carried out in the context of Industry 4.0 using artificial intelligence. In particular, these are the produced scientific publications:

- a solution to reduce the number of active stations in order to reduce the contention in the channel and save energy (Carlos Barroso-Fernández, 2023).
- The challenges ahead for using RAW as control plane for wireless deterministic networks (Bernardos, 2023).

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1. Introduction

In Industry 4.0 scenarios the latency and reliability requirements are of paramount importance for tasks that require real time operation, or high synchronization as remote control of factory robots. Having a network prone to huge jitter and latency harnesses the adequate behavior of the industrial services. Although recent advances in access technologies have pushed the capabilities of wired and wireless technologies, the heterogeneity of SDOs and technologies make challenging to have a system that conveys all technologies to provide end-to-end network guarantees across sites.

This document proposes the revise version of the initial system (Jorge Martín-Pérez, 2022) to ensure multi technology determinism in Industry 4.0 scenarios. The system accounts for heterogenous wireless access technologies (3GPP, IEEE 802.11, DetNet). The revised version of the system architecture elaborates in detail the connectivity layer and described the main concepts needed for ensuring E2E determinism.

The revised system proposes the division of the multi-technology connectivity layer into multi-SDO data plane (MDP) and multi-SDO control plane (MCP) to enable deterministic E2E industrial services. 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. The MCP builds on these programmable data plane enablers to compose E2E cross-domain deterministic services, by orchestrating the mechanisms of the various underlying technology domains.

The document is structured as follows. First, it presents the overall refined system design for an Industry 4.0. Then it explains in detail the main components of the multi-SDO control plane and the multi-SDO data plane. Finally, before concluding the document, it discusses the main updates with respect to the initial system architecture.

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2. Refined system design

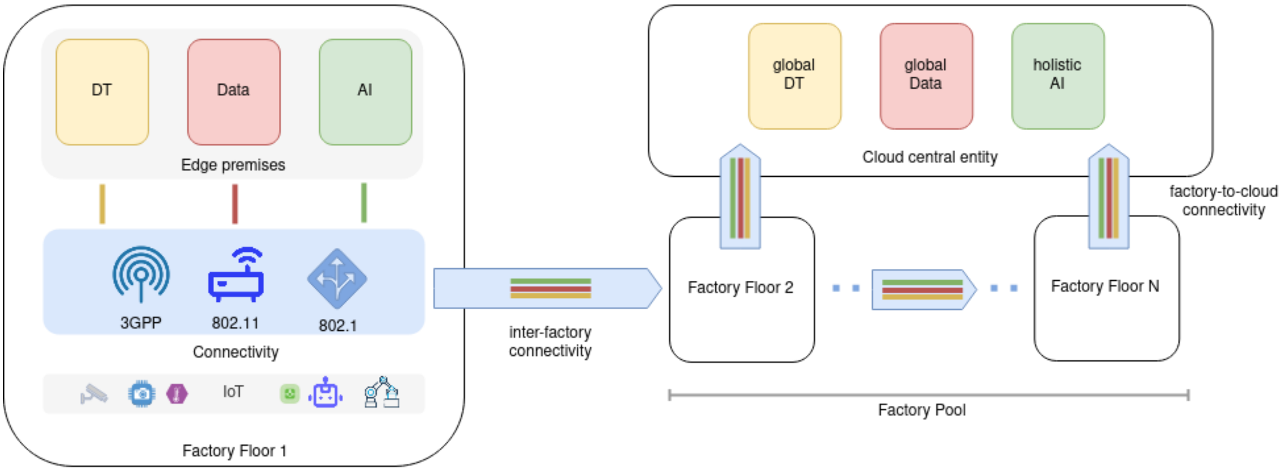

FIGURE 1: INITIAL SYSTEM DESING

This section outlines a modified version of the system design for the project, aiming to expand the original system to incorporate determinism across diverse wireless technologies within Industry 4.0 environments. Achieving this objective requires consideration of multiple Standard Development Organizations (SDOs) and their perspectives on determinism, specifically focusing on control plane and data plane mechanisms to fulfil latency and bandwidth requirements for Ultra-Reliable Low Latency Communications (URLLC) and deterministic services.

As illustrated in Figure 1, the initial system design assumed a scenario where a group of factory floors collaborates in executing Industry 4.0 tasks, such as quality control along factory lanes. Each factory floor comprises a connectivity layer with heterogeneous technologies, including 3GPP, 802.11, or 802.1—incorporating both wireless and wired technologies. The Internet of Things (IoT) devices within the factory floors, such as actuators, connect to the Edge premises over the connectivity layer to exchange information and receive commands related to factory processes.

The initial system design primarily focused on the inter-factory connectivity layer (top layer in Figure 1), responsible for transmitting information related to Digital Twins (DT), multi-purpose data, and AI communication. This document extends the initial architecture with a specific emphasis on the connectivity layer. Figure 2 depicts the refined system architecture, highlighting two key architectural aspects: the Multi-SDO control plane (MCP) encompassing management and control planes, and the multi-SDO data plane (MDP) representing the user-plane. The figure also identifies new architectural components and integration with existing state-of-the-art technologies.

The MDP serves as a "smart user-plane," encapsulating both user-plane (U-plane) and control-plane (C-plane) technologies from various standard definition organizations. Consequently, the MDP offers programmable packet/flow-level data plane mechanisms through their respective control-plane mechanisms. The MCP leverages these programmable data plane enablers to compose end-to-end cross-domain deterministic services and orchestrating mechanisms from various underlying technology domains.

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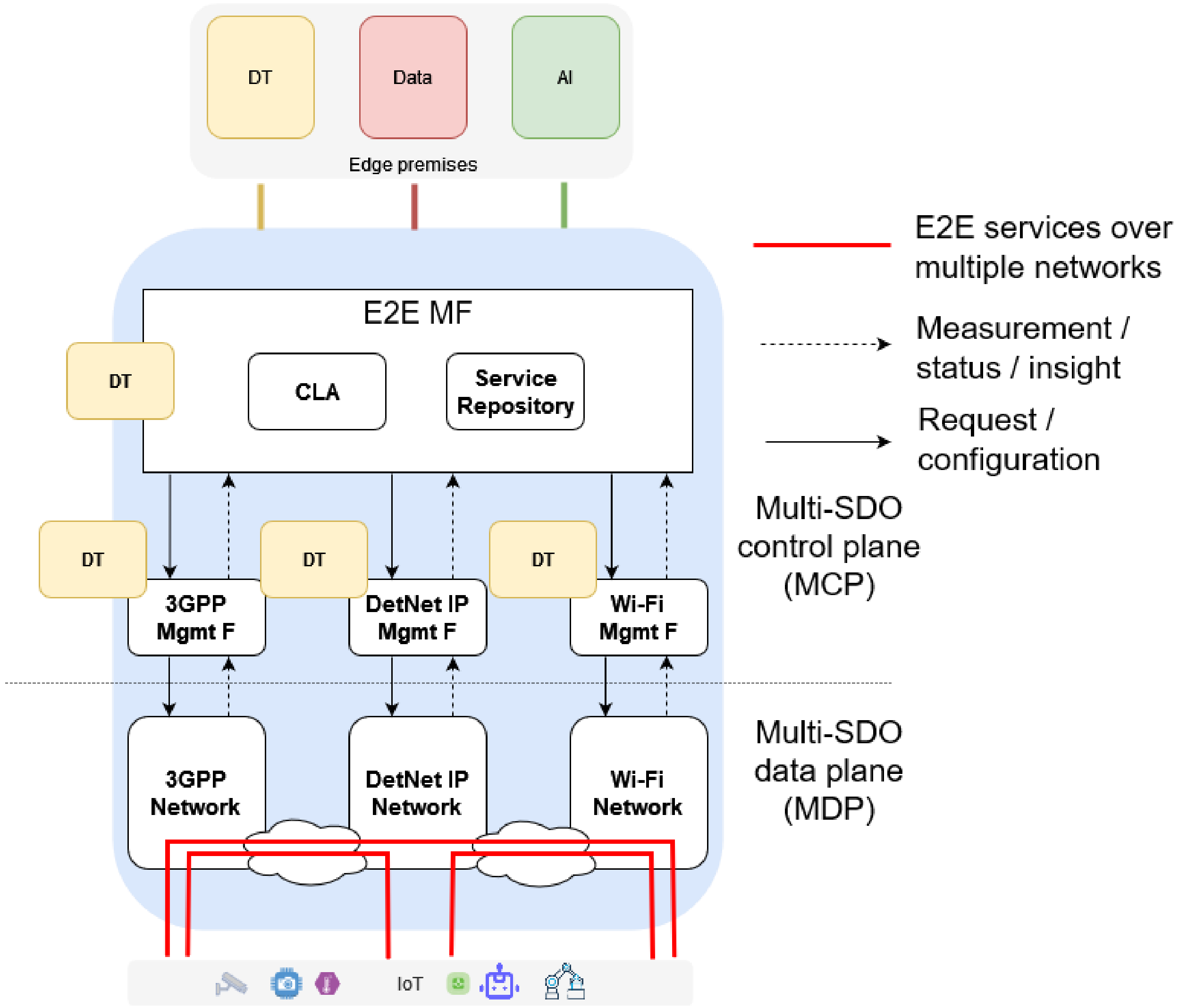

FIGURE 2: HIGH LEVEL REFINED SYSTEM DESIGN

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3. Multi-SDO Control Plane

3.1. Introduction

The architecture of the Multi-SDO inter-domain control plane (MCP) consolidates functionalities responsible for controlling and overseeing data plane services. Its purpose is to establish and guarantee an end-to-end deterministic service for concurrent data flows characterized by varying quality-of-service attributes. The MCP adopts a service-based architectural approach, segregating management capabilities into Management Services (MS), which are further structured into distinct Management Domains (MD). These Management Services interact through APIs uniquely defined for each respective Management Service.

3.2. Architecture design and components

Management Services and Managed Entities

The fundamental components and their associations within the service-oriented Multi-SDO inter-domain control plane (MCP) are depicted in Figure 3. A Management Service (MS) delivers a set of management capabilities (such as configuration, data, measurement, performance, analytics, control, etc.) with a specific scope, such as overseeing one or more Managed Entities (MEs) or providing services to other Management Services. In the context of the MCP, a Managed Entity (ME) is perceived as an architectural element within the Multi-SDO Data Plane (MDP).

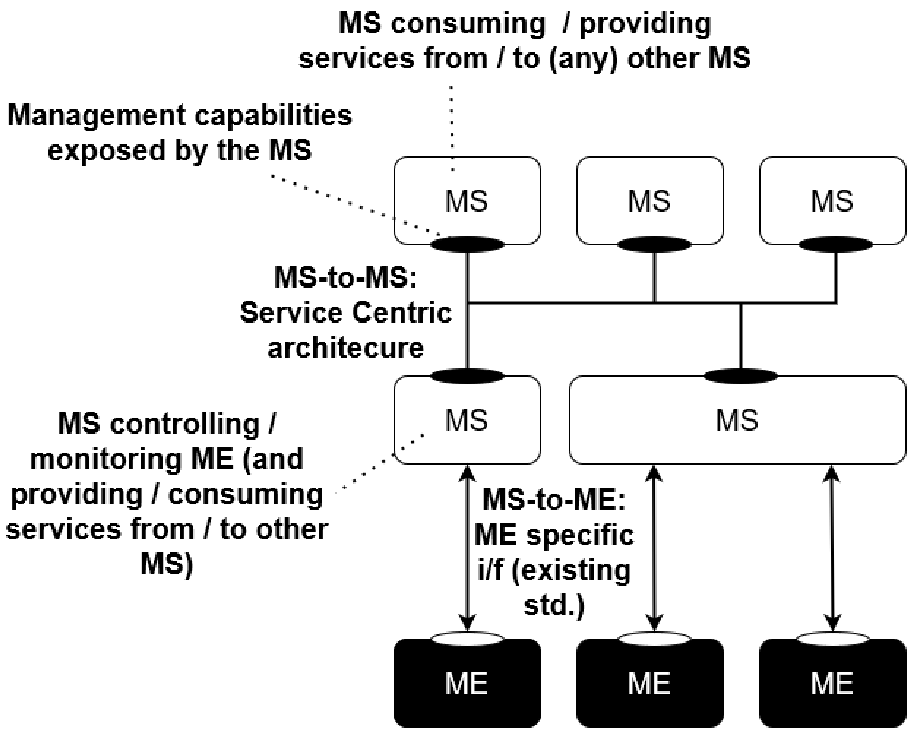

FIGURE 3: THE GENERAL BUILDING BLOCKS OF THE SERVICE-BASED MCP ARCHITECTURE: MANAGEMENT SERVICES, MANAGED ENTITIES AND THEIR RELATIONSHIPS

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An MS could offer the capability to provision deterministic services for a 3GPP network or deliver performance measurement services across a DetNet/IP network, with the latter being utilized by an analytics MS to assess service quality.

An ME might function as a 3GPP management component, facilitating the provisioning of specific Quality of Service (QoS) profiles for upcoming Protocol Data Unit (PDU) sessions.

In the MCP reference architecture, each Management Service provides its own API, accessible to any other MS. This implies that an MS's API is not tailored to a specific consumer, allowing for the separation of concerns and implementations related to management capabilities. In the MCP, an MS may or may not engage with one or more MEs, utilizing the ME's API. The ME's API might be defined in established standards like 3GPP, IETF, Wi-Fi 7, or any other external technical document beyond our system's control. Consequently, the integration of an MS with an ME is contingent on the ME's technology and may not adhere to the architectural guidelines followed by the rest of the system. Nevertheless, this technology-specific integration enables the proposed system to function as a framework for facilitating multi-domain deterministic services. As such, the integration between MSs and MEs constitutes a crucial implementation aspect that is outside the scope of this deliverable.

Management Domains

Within the MCP architecture, a Management Domain (MD) comprises a collection of interworking (federated) Management Services that share the same scope, such as operating over a common group or type of managed entities.

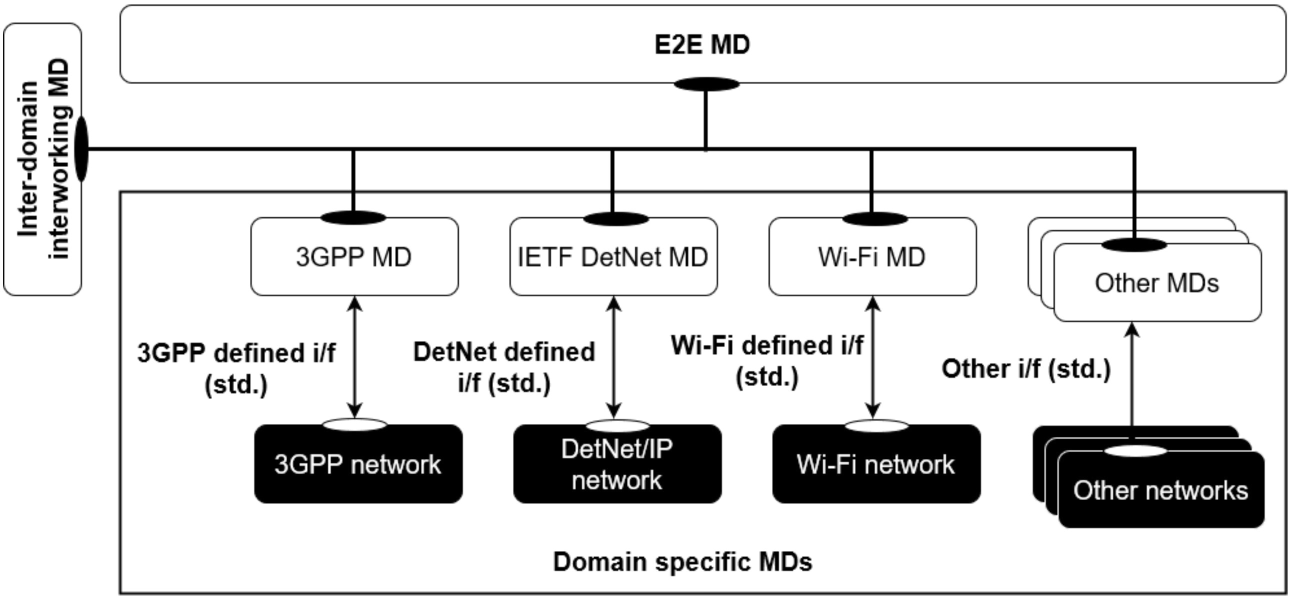

FIGURE 4: MANAGEMENT DOMAINS OF THE MCP ARCHITECTURE

Figure 4 outlines the MCP, introducing three categories of Management Domains:

1. Domain specific MDs

   These MDs are composed of management services (CM/PM/service/SLA/etc.) that are tailored to a specific network technology or an administrative domain governed by a

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particular network technology. The Management Services (MSs) within domain-specific MDs may engage with Managed Entities (MEs) in the underlying technology through ME-specific interfaces (e.g., 3GPP NEF), interact with other MSs within the same MD, and collaborate with MSs in the End-to-End (E2E) MD through the service-based architecture. Implementation-wise, the number of instances of domain-specific MDs corresponds to the variety of network technologies integrated into the system architecture. Presently, the architecture aims to integrate 3GPP, IETF DetNet, and Wi-Fi 7 as exemplary technologies. Despite the diversity of underlying network technologies, the service APIs of all domain-specific MSs should be technology-agnostic to facilitate scalability over other network technologies. Any technology-specific aspects of an MS within domain-specific MDs are encapsulated within the integration of the MS with its respective ME(s)

2. E2E MD

   Provides management services for creating and managing end-to-end deterministic services over multiple networks with potentially multiple technologies. MSs in this MD are interacting with other MSs in the E2E MD and MSs in all technology specific MDs via the service-based architecture. There is a single E2E MD in the system architecture.

3. Inter-Domain Integration MD

   MSs in this MD provide services for the proposed architecture itself (e.g., MS discovery and registration, high availability, resiliency, etc.). MSs in this domain interact with all other MSs in all MDs. There is a single Inter-Domain Integration MD in the system architecture.

Management Functions

Management Functions (Mgmt F) are entities designed to collaborate with the Management Services, contributing to the definition of functional blocks within the MCP architecture. Conceptually, a Mgmt F is a grouping of one or more Management Services, typically originating from the same Management Domain. The Mgmt F can be conceptualized as a cohesive functional unit that delivers its capabilities by leveraging the collective services offered by its constituent Management Services. From an implementation perspective, a Mgmt F may manifest as a deployable software unit suitable for orchestration on a cloud infrastructure.

3.3. Digital Twin as network predictability enabler

In this project, we are expanding the use of DT (Digital Twin) technology to offer two primary functionalities that facilitate management services associated with predictive analytics. Firstly, the DT anticipates the Quality of Service (QoS) Key Performance Indicators (KPIs) for a novel service request along a potential path within a single technological domain. Simultaneously, it forecasts the impact on the QoS KPIs for services already provisioned. Secondly, the DT predicts the End-to-End (E2E) QoS KPIs for a new service request that traverses multiple technological domains. In both scenarios, the key challenges lie in computing partial KPIs for a service that is supported by diverse technological domains.

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Digital Twin for Predictive Analytics

This service involves forecasting the KPIs for both new and existing traffic flows, such as TSN and Best Effort, within a designated technological domain. Two primary functionalities are outlined: initially, upon receiving a request (r), the DT calculates the KPIs for a traffic flow if it were established along a potential route based on the anticipated supporting traffic characteristics. Subsequently, the DT computes the KPIs for the given request and the additional KPIs for traffic flows (F) that are already established.

The following list of KPIs can be measured and quantified by the DT for the flow request under evaluation and the rest of established flows:

- Throughput (or data rate): Average volume of traffic (in Mb/s or Gb/s) at the input and/or output of a route (modelled as a queuing system) at a given time.
- Traffic loss ratio: Average percentage of traffic that is rejected due to lack of available capacity at a given time.
- Delay (or latency): Average of the elapsed time (in ms) that the traffic experiences when it traverses the defined route (modelled as a queuing system) from input to output at a given time.
- Jitter: Standard deviation of the elapsed time (in ms) that the traffic experiences when it traverses the defined route (modelled as a queuing system) at a given time.

For each of the described KPIs, two type of measurements can be obtained:

- Nominal values i.e., the actual values that the DT estimates for request r if it would be established.
- Delta values i.e., the difference (increment or decrement) that the DT estimates comparing the KPIs computed before and after establishing request r.

Typically, nominal values can be computed for the request r, while delta values are computed for the existing set of flows F. However, depending on the specific KPI, service type and use case, the set of available KPI metrics and measurements can change. In any case, the DT is always able to provide relevant and accurate QoS estimation data that can be used for decision making.

This Digital Twin model can receive inputs from:

- Service Automation: Service DB, and Service provisioning and decommission notifications.
- Topology Exposure: Topology DB and Topology update notifications.
- Measurement Collection: Traffic and KPI Measurements.
- Service Automation: Request to compute the E2E KPIs
- Resource and Capability Exposure: resource characteristics

The predictive analytics Digital Twin outputs (E2E KPI predictions) will be later used for Service Automation.

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E2E Predictive Digital Twin

This DT consists in predicting the E2E KPIs of new traffic flows (TSN, BE, etc). Two main functionalities are identified: first, the DT receives a request (r) to compute the KPIs of a traffic flow if it was established on a candidate route traversing several technological domains, together with the partial KPIs for each of these domains.

This Digital Twin model can receive inputs from:

- Service Automation: Service DB, and Service provisioning and decommission notifications.
- Topology Exposure: Topology DB and Topology update notifications.
- Measurement Collection: Traffic and KPI Measurements.
- Service Automation: Request to compute the E2E KPIs

The E2E predictive Digital Twin outputs (KPI predictions) will be later used for Service Automation

3.4. Architecture definition

The Management Services within the Inter-Domain Integration MD are envisioned to encompass the following functions:

- **Registry**: Maintains a record of the available Management Services along with their implemented capabilities.
- **Discovery**: Facilitates the discovery of other Management Services by allowing them to be found based on requested capabilities.
- **High Availability**: Guarantees that the Management Services remain consistently accessible, ensuring the continuous provision of their capabilities.

The Management Services within the End-to-End (E2E) MD are conceived as follows:

- **Time Sync Management**: Establishes and sustains End-to-End time synchronization across diverse domains.
- **E2E Monitoring**: Aggregates End-to-End Key Performance Indicators (KPIs) from measurements at the domain level, enhancing awareness of E2E services within the designed system.
- **E2E Learning Orchestrator**: Oversees the comprehensive learning process spanning different domains.
- **DT Predictive Analytics**: Predicts the E2E KPIs for new traffic flows (TSN, BE, etc.).
- **E2E Path Computation**: Computes routes throughout the E2E domain using the domain-level path computation service.
- **E2E Service Ingestion**: Manages requests for E2E services from system consumers.
- **E2E Service Automation**: Delivers End-to-End closed-loop service automation and conflict resolution across all domains, ensuring continuous compliance with the requirements of E2E deterministic services.
- **E2E Service Exposure**: Exposes service information from the E2E perspective to system consumers.

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- **E2E Topology Exposure**: Reveals topology information from the E2E standpoint, abstracting the topology details for all domains.
- **E2E Resource Manager**: Initiates requests for resource configuration across all participating domains in delivering an ingested service.

The Management Services within each Domain-Specific MD are outlined below:

- **Time Sync**: Reveals and configures time synchronization capabilities within the domain.
- **Measurement Collection**: Grants access to domain-level measurements with varying scopes (e.g., packet, data flow, service) and granularities (e.g., time, link/path aggregation).
- **Learning Manager**: Interacts with the AI/ML Resource Orchestrator, as well as the AI/ML Model and Dataset Repositories and Registries, to fetch AI/ML models/datasets as needed and maintain the currency of the AI/ML Model Repository/Registry.
- **Learning Orchestrator**: Coordinates the local training of AI/ML Models within a specific domain.
- **DT Predictive Analytics**: Forecasts the Key Performance Indicators (KPIs) for new and existing traffic flows (TSN, Best effort, etc.) within a designated domain.
- **Dataset Repository**: Stores datasets used for AI/ML operations, including model training.
- **Dataset Registry**: Contains dataset characteristics (e.g., size, domain, input features, privacy requirements, data statistics information).
- **AI/ML Model Repository**: Houses various types of AI/ML models for specific tasks.
- **AI/ML Model Registry**: Records characteristics of AI/ML models, such as structure, input/output format, complexity level, associated datasets used for training (if any), and the latest training/update operation (if any).
- **AI/ML Resource Orchestrator**: Locally operates within each domain, orchestrating computational and networking resources.
- **Path Computation**: Computes routes for domain-level services.
- **Service Automation**: Offers closed-loop assurance for domain-level services through domain-specific integration.
- **Service Exposure**: Exposes information about provisioned domain-level services within the underlying domain.
- **Topology Exposure**: Reveals topology information from the underlying domain.
- **Capability Exposure**: Exposes deterministic capabilities available within the domain.
- **Resource Exposure**: Provides the current status of available resources within a domain.

Resource Configuration: configures the resources of the corresponding domain using domain specific integration.

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4. Multi-domain Data Plane

This section presents the data plane architecture, outlining how various domains can collaborate within the data plane and interface with the MCP to facilitate end-to-end deterministic services. Since the Multi-SDO Data Plane (MDP) relies on a variety of pre-existing network technologies, the emphasis of the MDP architecture lies in (1) integrating these technologies at domain boundaries and (2) rendering them programmable from an end-to-end perspective to achieve cross-domain determinism.

4.1. MDP architecture concepts

Figure 5 illustrates the fundamental architectural principles of MDP, employing a blend of foundational technologies (such as 3GPP, IETF DetNet, Wi-Fi).

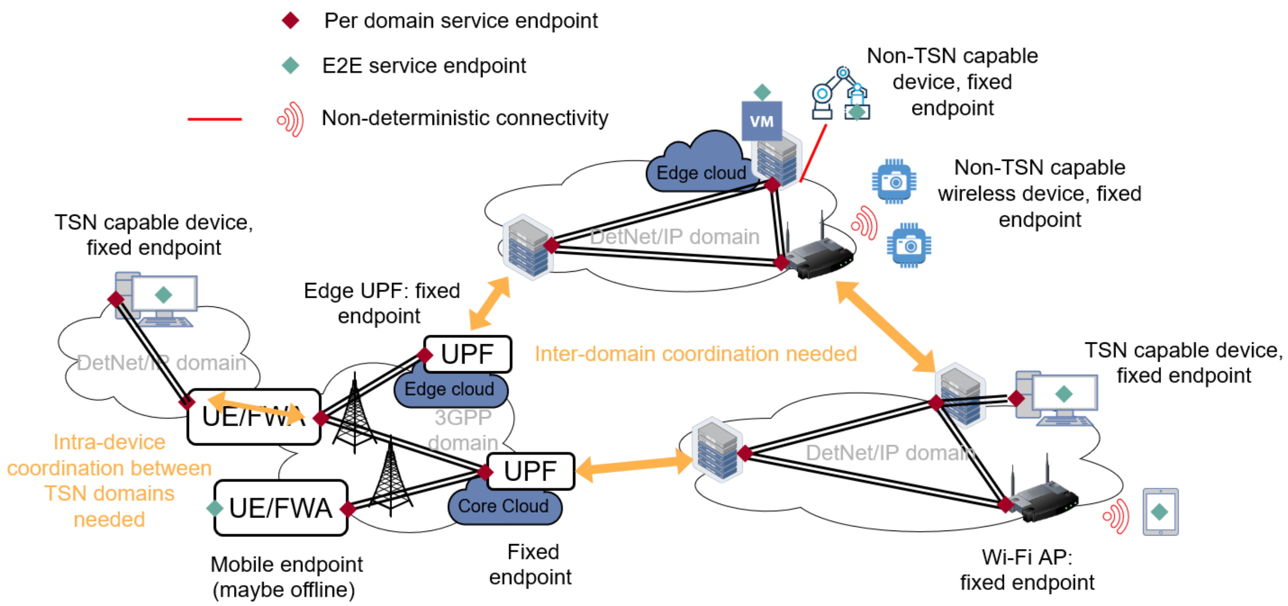

FIGURE 5: ARCHITECTURAL CONCEPT OF THE MDP

The key architectural concepts of MDP include the following:

- **End-to-End (E2E) Deterministic Service Flow:** A logical connection traversing one or more domains with deterministic quality-of-service characteristics.

  Requirement: User plane packets mapped to the same E2E deterministic service flow should receive consistent treatment in the data plane, and packets within this flow must not experience reordering.

- **E2E Service Endpoints:** Logical endpoints of E2E deterministic service flows.

  Implementation: Executed by the network/technology stack of the hosting domain

- **Per domain service endpoint:** Logical endpoints specific to a domain-level service, aligning with the service concept as defined within the respective domain.

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Examples: In 3GPP, service endpoints include the UE and the UPF, and a domain level service is represented by a PDU Session.

- **Inter-domain coordination:** Encompasses potential mechanisms applied at data plane interchange points between domains, facilitating the transfer of user plane packets from one domain to an adjacent domain.

Implementation:

  - **Example 1**: Harmonized configuration of adjacent domain-specific endpoints, ensuring consistent treatment of user plane packets in transit.
  - **Example 2**: Utilization of in-line packet-based mechanisms, such as packet marking, to maintain consistent mapping and processing of user plane packets across domains.

- **Intra-device coordination:** a set of mechanisms applied within the network and technology stack of a single device or equipment to facilitate deterministic packet processing.

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5. Main updates from the initial system design

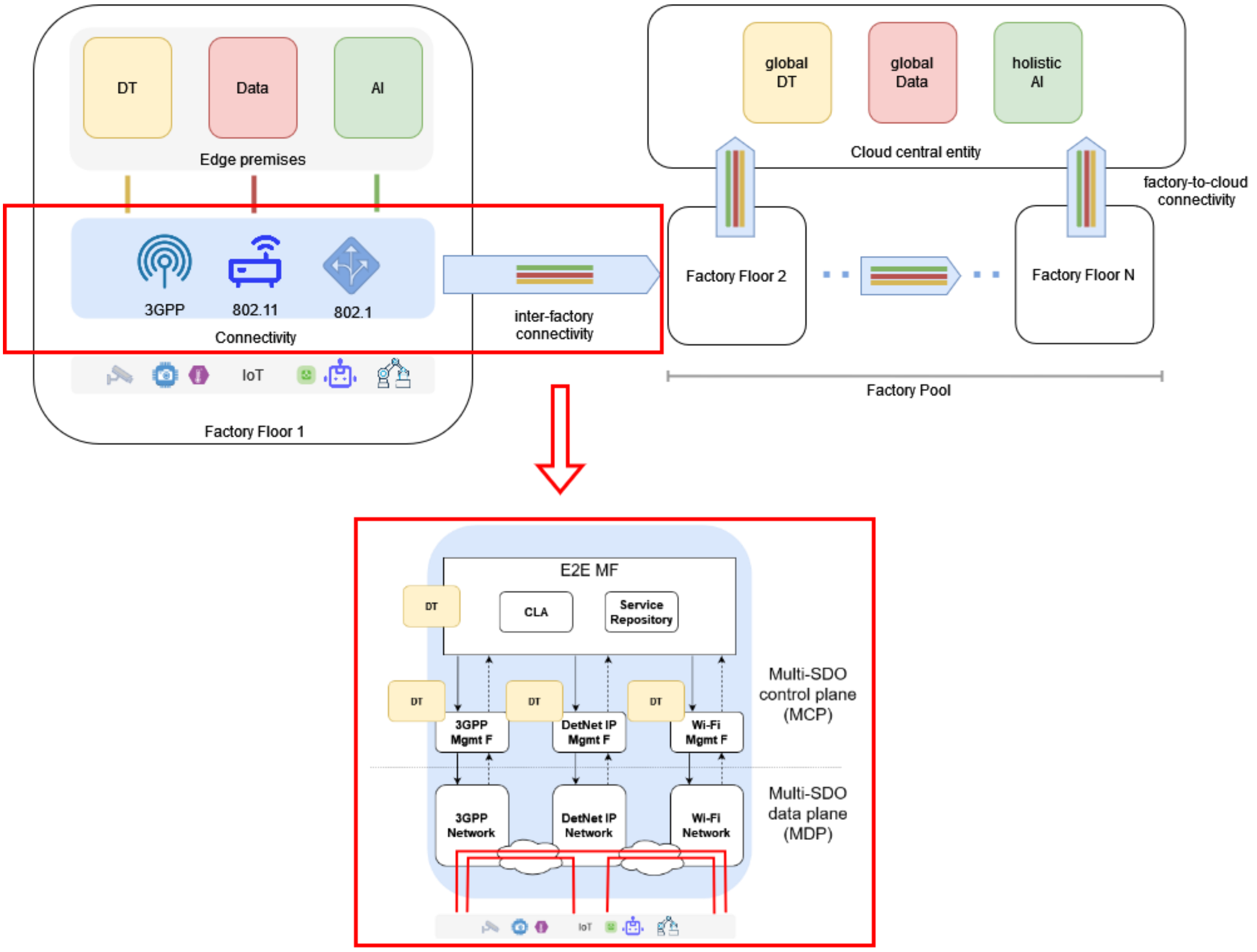

FIGURE 6: INITAL SYSTEM ARCHITECTURE EXTENSION

Figure 6 illustrates the main updates of the initial system architecture. Working towards realizing the vison of E2E deterministic services over multiple technologies and inter-factory scenarios, we extended the initial system architecture by:

- Proposing a detailed design of the connectivity layer to support multi-technology determinism. We divided the connectivity layer into:
  - Multi-SDO Control plane (MCP) that can offer E2E service management via the E2E Management Function
  - Multi-SDO Data Plane (MDP) that is directly configured by the MCP and interacts with the factory floor devices in order to ensure the E2E guarantees
- Extended the DT concept, to address predictive analytics of E2E QoS KPIs

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6. Conclusions

This document presents the revised system design of a multi-SDO platform in Industry 4.0 scenarios. The proposed system accounts multi-SDO technologies for wireless access on the factory floor, and proposes the usage of multi-SDO data plane, multi-SDO control plane and E2E control plane that can provide end-to-end guarantees in industrial services as robotic remote control.

The core of the proposed system is the E2E control plane that can offer different services such as time synchronization, packet replication or topology exposure over the multi-SDO technologies to ensure the E2E determinism. Additionally, the revised system extends the Digital Twin definition so it can be applied per technical domain and so it can offer predictive analytics.

7. References

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