UNICO I+D Project

6G-DATADRIVEN-04

6G-DATADRIVEN-04-E6

Initial system architecture

Abstract

This report describes the required system architecture to achieve reliable and deterministic network connectivity in Industry 4.0 environments. The proposed architecture relies on the use of Digital Twins to reproduce and predict the network behaviour in factory floors, and have end-to-end guarantees regarding latency and jittter. The system considers multi-SDO scenarios with multiple access technologies, and identifies the required extensions to make in more advanced stages of the project.

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List of Acronyms

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

ADMM: Alternative Direction Method of Multipliers

AI/ML: Artificial Intelligence / Machine Learning

DetNet: Deterministic Networking

DNN: Deep Neural Network

DRL: Deep Reinforcement Learning

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

NOMA: Non-Orthogonal Multiple Access

NPN: Non Private Network

ROS: Robot Operating System

RAW: Reliable and Available Wireless

SDN: Software Defined Networks

SDO: Standards Developing Organization

TSN: Time-Sensitive Networks

URLLC: Ultra-Reliable Low Latency Communications

Resumen Ejecutivo

Este documento proporciona una versión inicial del sistema diseñado 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 un sistema que proporciona conectividad fiable en entornos de industria 4.0;
- la incorporación de múltiples SDOs en el diseño del sistema;
- el uso de DTs para imitar y predecir el comportamiento de la conectividad industrial; y
- la mención de las extensiones necesarias para hacer factible el despliegue del sistema propuesto en escenarios con tecnologías de acceso heterogéneas.

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 que permite usar inteligencia artificial para mitigar la interferencia inalámbrica en el control remoto de un brazo robótico (Groshev, Martín-Pérez, Guimarães, Oliva, & Bernardos, 2022), (Milan Groshev, 2022); y
- la formulación del problema de despliegue de servicios de robots para entornos de industria conectada (Khasa Gillani, 2022).

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 initial version of the system design for 6G-DATADRIVEN-04. The document details the components of the system and explains the required extensions for its implementation.

The main contributions of this deliverable are:

- the proposal of a system design providing reliable connectivity for Industry 4.0 scenarios;
- the consideration of multi-SDO connectivity in the system design;
- the use of DTs to mimic and reproduce the network behaviour in industrial environments; and,
- detailing the necessary extensions to allow the deployment of the proposed system design in scenarios with heterogeneous access technologies.

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 mitigate Wireless interferences in remote control of robots (Groshev, Martín-Pérez, Guimarães, Oliva, & Bernardos, 2022), (Milan Groshev, 2022); and
- the problem formulation of services deployed in connected Industry (Khasa Gillani, 2022).

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1. Introduction

In Industry 4.0 scenarios the latency 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 behaviour 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 an initial system design to provide multi-SDO support for Industry 4.0 scenarios. The system accounts for heterogeneous access technologies with diverse operation capabilities to meet latency sensitive requirements in industrial services.

The proposed system uses proxies to interact with different access technologies, and DTs to ensure an adequate end-to-end behaviour of the network. A pool of factory floors exchange monitoring flows to periodically report the network status, and the corresponding DTs mimic and predict the incoming behaviour of the network to react upon possible misbehaviour.

The document is structured as follows. First, it presents the overall system design for an Industry 4.0 scenario. Then, it explains how the system encompasses the Multi-SDO support. Later, it gets into the details on how the DTs serve to understand the network behaviour to react and take the necessary mitigation measurements. Lately, it presents the extension mechanisms that future stages of this project will tackle. And last of all, it concludes the present deliverable.

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2. Overall system design

This section presents an initial version of the overall system design of the project. The goal is to design a system embracing different connectivity technologies across factory floors in Industry 4.0 scenarios. To that aim it is necessary to consider multiple SDOs and their vision regarding connectivity guarantees, in particular, the mechanisms and requirements established by multiple technologies to meet latency and bandwidth requirements for URLLC and DetNet services.

As depicted in Figure 1, the system assumes a scenario where a pool of factory floors cooperate to perform Industry 4.0 tasks as quality control along the factory lanes. Each factory floor consists of a connectivity layer with heterogeneous technologies as 3GPP, 802.11 or 802.1; i.e., either wireless or wired technologies. The IoT devices of the factory floors – e.g., actuators – connect to the Edge premises over the connectivity layer to exchange information and receive commands for tasks related to the factory processes.

Figure 1 shows the inter-factory connectivity layer carries information related to Digital Twins (DTs), multi-purpose Data (e.g., monitoring), and AI communication among factory floors. The former exchange of data is the one that we focus on, i.e., the exchange of DT data among factory floors.

This system design pays special attention to network DTs that capture the network behaviour at both factory floor level, and global level. In particular, it envisions a factory-to-cloud connectivity that exchanges the local DTs to a central Cloud that holds a global DT of the Industry 4.0 pool of factory floors. In particular, the global DT contains an end-to-end vision of the internet connectivity in the pool of factory floor, considering the heterogeneous connectivity of each factory floor: 3GPP, 802.11 or 802.1 connections.

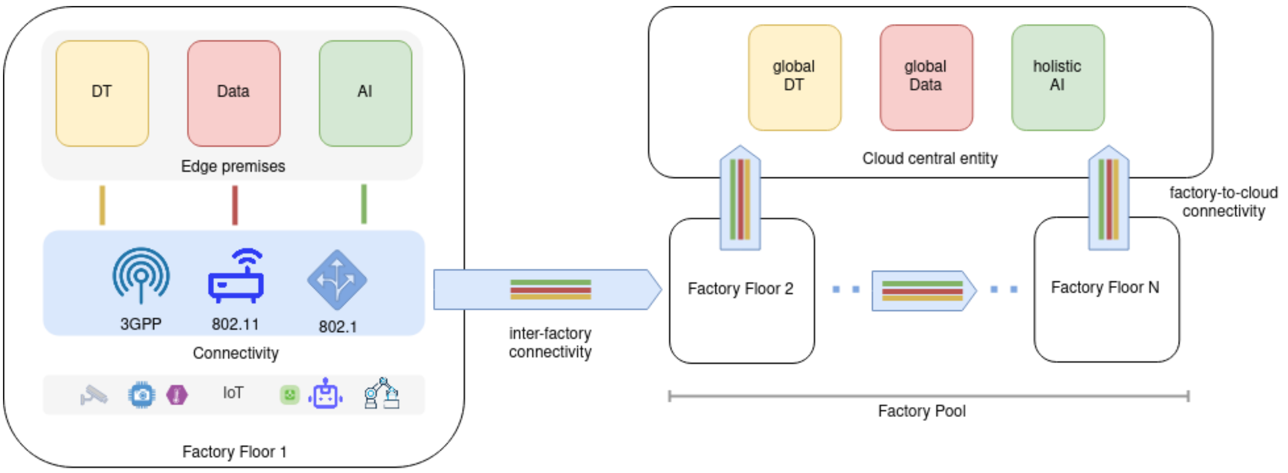

FIGURE 1: OVERALL SYSTEM DESIGN

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3. Multi-SDO support

As mentioned in the prior section, the goal of the proposed system design is to embrace multiple technologies for internet connectivity. In internet connections there exist multiple Standards Developing Organizations (SDOs) as the Institute of Electrical and Electronics Engineers (IEEE), 3rd Generation Partnership Project (3GPP), and Internet Engineering Task Force (IETF). All of them define the protocol and internet architectures to ensure quality in the Internet deployments.

The most recent access technologies proposed by these SDOs are: 5G networks, 802.11ax, and DetNet in 802.1TSN (Time-sensitive networking). These three technologies promise Ultra-Reliable Low Latency Communications (URLLC) and determinism at the network level to ensure that latency-sensitive services as robotic remote control meet the expected service requirements.

On top of these access technologies, the IETF RAW (Reliable and Available Wireless) is standardizing a common framework to convey the heterogeneity in the access network to have a holistic management and vision of the network behaviour. That is, IETF RAW proposes a set of interfaces and entities that encompass the network heterogeneity to provide end-to-end guarantees in the communication.

However, it is yet to be done how to consider IETF RAW together with the heterogeneous internet access and latency mechanisms to have network DTs and AI management in latency-sensitive and reliable services for Industry 4.0. In the following we provide a high-level vision on how the proposed system design tackles the aforementioned challenge to achieve multi-SDO support.

To achieve multi-SDO support, the DATADRIVEN-04 system defines proxies that serve as translators of the requirements of an end-to-end service. There is a dedicated proxy per each Internet access technology, e.g.: 3GPP 5G, 802.11ax or 802.1TSN. Each proxy serves not only as a translator but as an interface to configure the multi-SDO devices to have the desired internet connection in a factory floor.

For a robotic arm remote control service, it is important to have low latency and negligible jitter between the remote server and the robotic arm that it controls. Interferences and packet delays due to the queues induce large latencies that harness the timely delivery of packet. To achieve an URLLC for the remote control of a robotic arm, the Factory Floor must be aware of the network behaviour under the current load (e.g., working hours). Once the network status is known, the 3GPP proxy may receive resources scheduling updates to prioritize the transmission of packets related to the remote control, the 802.1TSN switch may receive traffic shaping rules, and an 802.11ax router can obey to OFDMA scheduling rules to give more RUs for the transmission of remote control commands.

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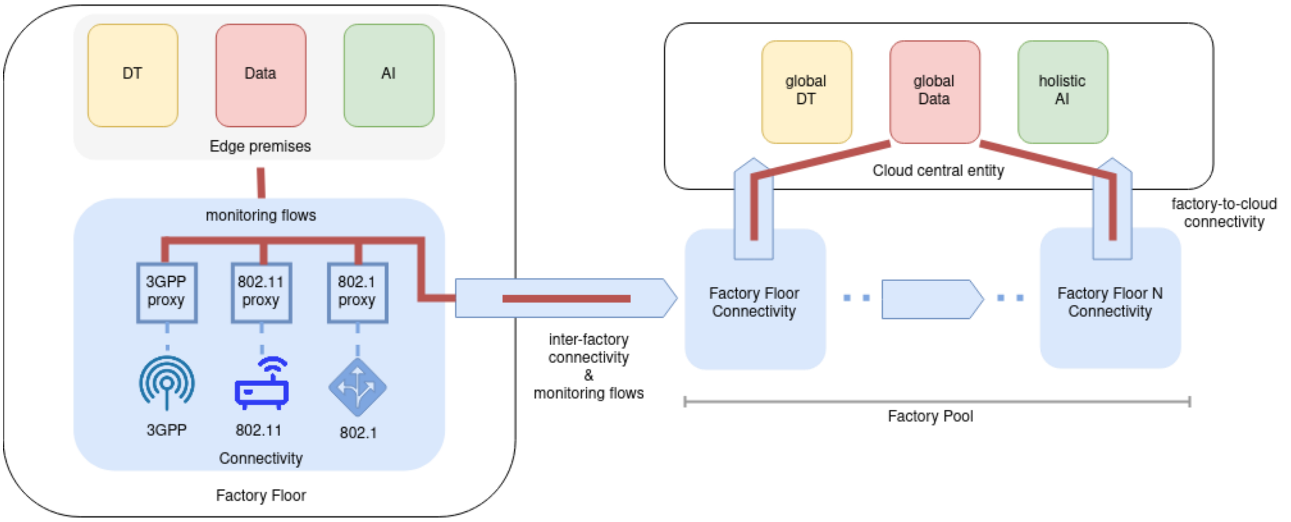

FIGURE 2: MULTI-SDO PROXIES AND MONITORING FLOWS

Figure 2 illustrates the multi-SDO proxies explained in the prior paragraph. The idea is that depending on the service needs in terms of bandwidth, latency or jitter; the Factory floor can interact with multi-SDO technologies to ensure the expected quality of service of an application.

To know whether the packets are being scheduled and transmitted as expected, the proposed system sends monitoring flows reporting the proxies' status towards the Data entity in the Edge premises. Then, the Data entity exposes the buffer size, latency of each SDO connectivity element, and other useful metrics to assess the correct behaviour. Consequently, the factory floor may decide to update traffic and prioritization rules for each SDO technology to meet the requirements.

For the proposed system assumes that factory floors may cooperate to perform tasks as quality control, the proposed system also considers the exchange of monitoring flows over inter-factory connectivity to exchange the inter-site network status. Consequently, each factory floor may update the configuration of SDO entities that serve as egress point to exchange information, so possible bottlenecks in the inter-factory connectivity are mitigated.

In the same spirit as the inter-factory floor connectivity, each factory floor exchanges the monitoring flows with the Cloud central entity, so the latter has a holistic report on the network performance across the factory pool. The factory-to-cloud connectivity carries such monitoring flows, and stores in the global Data entity information regarding the inter-factory floor SDO elements as: buffer sizes, per flow information (e.g., jitter, delay, 90^{th} percentile delay), bandwidth allocation, traffic shaping strategies, etc.

As a result, the proposed system presented in Figure 1 and Figure 2 provide a multi-SDO support through the usage of proxies and exchange of monitoring flows that carry information about the network status. In the next deliverables we will detail how the proxies act as translator/interfaces with the multi-SDO devices, e.g., how they convert a latency requirement from a service to queueing policies depending on the URLLC, DetNet, or TSN capabilities of the devices.

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4. Network Digital Twins

One of the most relevant elements of the proposed system is the factory floor DT. In the initial system design, the DT is intended to provide a mirroring of the network behaviour when using multi-SDO devices. Thanks to the DT it is possible to simulate the network behaviour of the factory floor premises.

Figure 3 illustrates in yellow the DT entity running within the premises of the factory floor. The DT entity embeds both the DT of the factory floor, and the associated analytics. The DT is a model that captures the behaviour of the factory floor network, and its different multi-SDO devices. For example, it may resort to simulations to mimic the connectivity between TSN switches and URLLC NR antennas, or even resort to queueing theory models as Jackson queues of G/G/1 systems.

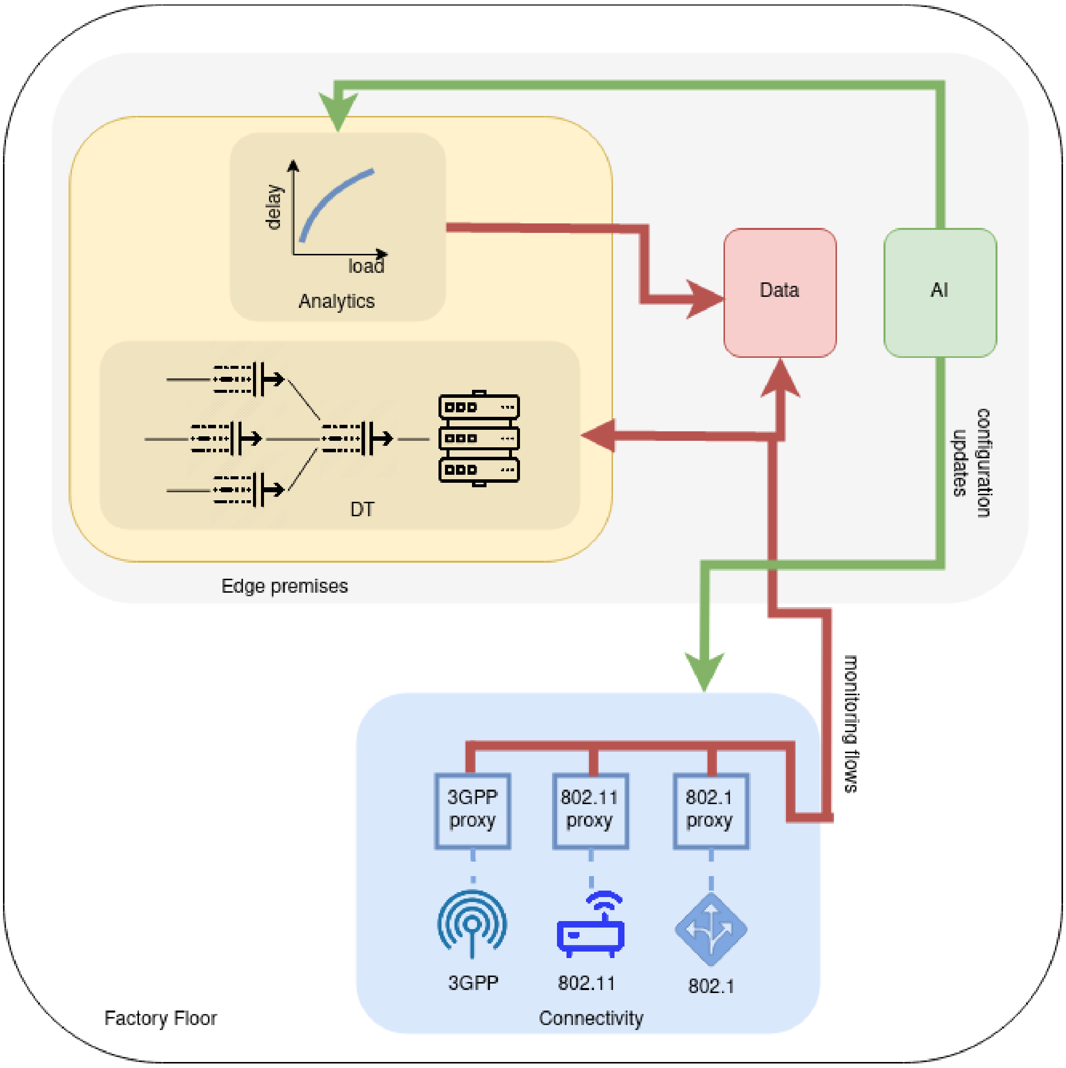

FIGURE 3: FACTORY FLOOR NETWORK DIGITAL TWIN

The DT receives data from the multi-SDO proxies and also from the Data entity at the edge premises. The connectivity layer exchanges monitoring flows that are used by the DT (e.g., a network simulator) to have input with which it models the network behaviour. The execution of the DT results into an

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output that yields relevant metrics as the network congestion, which is later reported and stored in the Data entity to monitor the network status.

With the network DT, the DT entity derives analytics as the system delay based on the network load at the factory floor. Such analytics are achieved through AI models that provide estimations about the network performance.

The analytics and DT execution is performed in a closed-loop fashion that is invoked upon the arrival of new reports within the monitoring flows. Namely, if a 5G connectivity begins to have high wireless interference, the 3GPP proxy will report it to the Data Entity, which will trigger the analytics and DT execution to tell whether the current services are supported by means of requirements with such interferences. If it is not possible to meet the requirement (e.g., <10ms RTT), the AI entity will yield instructions to mitigate the network degradation, and issue updates as the queueing policy, or user admission at the 3GPP proxy.

4.1. Global DT for the pool of factory floors

The factory floor DT enables the network control at a local level. However, in the case the pool of factory floors requires the exchange of information and AI coordination for an holistic management, it is necessary to define a cooperation among them. To that aim, in this section we introduce how the Central Cloud entity of the proposed system hosts and holistic DT of the end-to-end connectivity across factory floors.

Figure 4 shows the proposed scheme. The idea is that each factory floor exchanges the monitoring flows with the global Data entity hosted at the Cloud central entity. Such global Data entity will report to the global DT the status of the network at the different factory floors. By using the whole set of monitoring flows, it is possible to build a global DT that captures the behaviour of the whole pool of factory floors in an end-to-end fashion.

The global DT can tell whether a remote control from one factory floor to another will meet the required latency metrics. It can rely either on a holistic model/simulation of the factory pool, or rely on the local DTs at each factory floor, complemented with the inter-connectivity topology that stitches the factory floors.

Similar to the local DT at each factory floor, the holistic AI monitors whether the analytics reports are aligned with the expected latency/bandwidth guarantees. In case the end to end connectivity does not meet them, the holistic AI instructs each local AI the necessary changes at each multi-SDO device to meet the service requirements. For example, the holistic AI could realize that the jitter in a multi-factory floor stream is too large and instruct the corresponding proxy requests to each factory floor (e.g., to update the queuing and priority policies).

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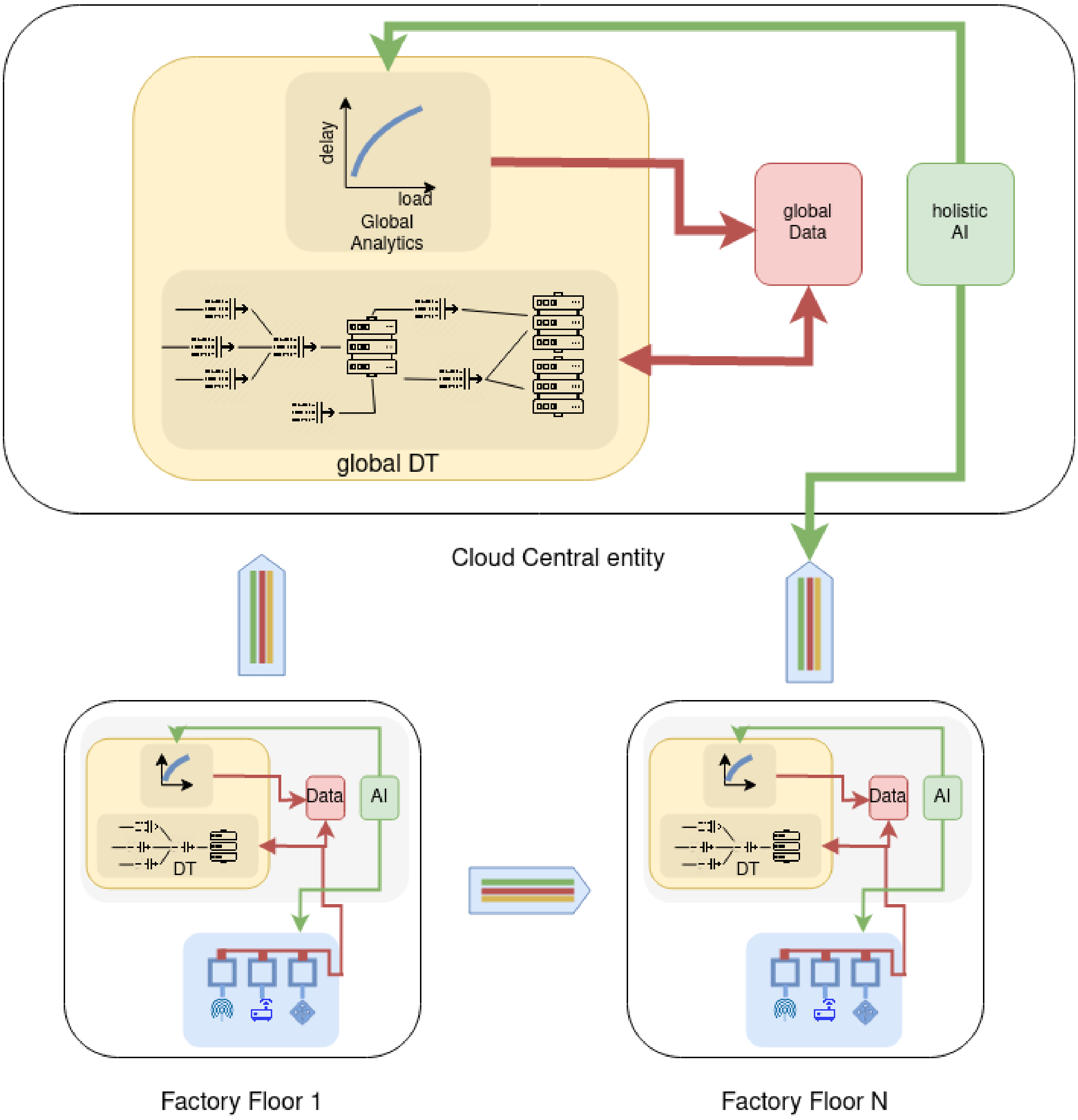

FIGURE 4: GLOBAL DT AND INTERACTIONS WITH FACTORY FLOOR DTS

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5. Extension mechanisms

The presented system inter operates with heterogeneous connectivity technologies, namely, it explicitely mentions 802.11ax, 5G and 802.1TSN technologies. All of these can provide certain levels of determinism and reliability regarding the communication latency. However, this is not the case for legacy technologies that were designed for best-effort purposes.

This project aims to extend the support for legacy technologies using mechanisms as SDN to manipulate the routing, queueing, and priority policies at each switch/router. Additionally, it will consider the interoperability of other access technologies as older versions of 3GPP and 802.11, so as to have a balanced approach. This is, the lack of URLLC and DetNet support in those technologies are going to mitigated through mechanisms that prioritize such traffic over the traffic attended by more recent technologies that can exploit solutions as short transmission for URLLC.

Additionally, the future stages of this project will investigate how to contribute to IETF RAW to have an end-to-end determinism in the networking communications across factory floors.

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6. Conclusions

This document presents the system design of a multi-SDO platform in Industry 4.0 scenarios. The proposed system accounts for multi-SDO technologies for internet access and proposes the usage of proxies to have interoperability and provide end-to-end guarantees in industrial services as robotic remote control.

The core of the proposed system is the usage of DTs at each factory floor to understand the behaviour of the network deployment at each local premise. Additionally, the system envisions an holistic DT equipped with Analytics and AI assisted modules to instruct policy updates in the network underneath, and meet the expected latency requirements in the end-to-end connection.

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