Digital Twinning for 6G Teleoperated Driving: The 6G-TWIN Vision

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***Abstract*—Previous efforts focusing on 5G support for teleoperated driving mainly targeted communication challenges and goals, developing and evaluating key 5G enabling technologies such as network slicing, seamless cross-border roaming, Multi-access Edge Computing (MEC) enabled distributed computing, or predictive Quality of Service/Experience (QoS or QoE). However, these goals are at odds with energy conservation, with energy savings being a major goal of modern mobile broadband networks. This poses significant challenges, calling for new thinking and new system architectures that go beyond the current 5G Service-Based Architecture (SBA). In this paper, we present the vision of the European 6G-TWIN project for leveraging digital twins to provide a safe and efficient communication infrastructure for teleoperated driving, along with a demonstrator design to validate the project's solutions.**

I. INTRODUCTION

6G-TWIN is a European project which envisions future 6G architectures as a cyber-physical continuum in which Digital Twins (DTs) of the physical world provide a safe sandbox for closed-loop zero-touch network automation. At its core is a federated simulation framework orchestrating simulators. In turn, each simulator contains a model serving as a digital replica of a network element, topology, or service – mirroring the physical world to provide what-if analyses and predictive control to optimization algorithms.

One of the key use cases of 6G-TWIN is teleoperated driving, which is a prime example of a highly dynamic and safety-critical application that will benefit from the envisioned architecture. Here, a car driving on the road is controlled via a 6G network by a remote human operator who is monitoring the vehicle's environment via a multitude of high-definition sensors (camera, LiDAR, etc.) and controlling its actuators at up to freeway speeds. This requires ultra-reliable and low-latency communication, but also requires balancing these goals with economic and environmental sustainability. Teleoperated driving is thus a classic example of a use case that is difficult to model and optimize using traditional methods, but which can benefit from the predictive capabilities of a Network Digital Twin (NDT) [1], [2].

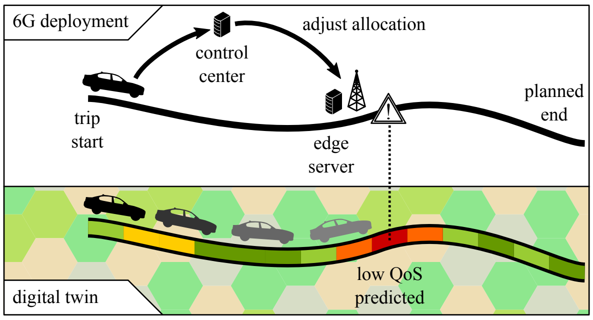

Figure 1. Envisioned 6G-TWIN system for teleoperated driving: Before the actual journey begins, the vehicle is first driven inside the digital twin, which identifies (potentially) necessary adjustments to the network and edge computing infrastructure.

Previous efforts focusing on 5G support for teleoperated driving mainly targeted communication challenges and goals, developing and evaluating key enabling technologies such as network slicing, seamless cross-border roaming, Multi-access Edge Computing (MEC) enabled distributed computing, or predictive Quality of Service/Experience (QoS or QoE) [3], [4]. However, these goals are at odds with energy conservation, with energy savings being a major goal of modern mobile broadband networks. This poses significant challenges, calling for new thinking and new system architectures that go beyond the current 5G Service-Based Architecture (SBA). 6G will go beyond communications with an increasing trend of embedding Artificial Intelligence (AI) into distributed communication networks to cope with increasing network complexity and dynamic network management [5], [6]. 6G will facilitate cross-functional missions combining communications, computation, positioning, and sensing in an NDT environment in order to satisfy service/application requirements before being deployed at a large scale with cost and energy effectiveness.

In this paper, we present the vision of 6G-TWIN for leveraging DTs to provide a safe and efficient communication infrastructure for teleoperated driving, along with a demonstrator design to validate the project's solutions.

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II. DIGITAL TWINNING FOR 6G TELEOPERATED DRIVING

The concrete situation we are envisioning is illustrated in Figure 1: A car is teleoperated via a 6G network relying heavily on Virtual Network Functions (VNFs). Here, we assume that teleoperation also requires data fusion and preprocessing on edge servers in order to overcome the limited computing capabilities of the vehicles while limiting the amount of information transmitted (i.e., reducing network load). We further assume that edge servers at different locations can be turned off during periods of inactivity (e.g., rural areas). Before the actual journey can begin, the vehicle is first driven inside the federated simulated framework to investigate whether the network provides the necessary edge computing capacity levels along the route. If gaps are identified, additional resources (e.g., edge computing capacity, VNFs) are deployed within the simulation framework until the virtual journey is successfully completed. The resulting optimal configuration parameters can then be sent to the corresponding controllers in charge of interacting with the actuators in the real world.

This is a multi-objective optimization problem, as the network must automatically balance: (1) optimal resource allocation of computing capacity along the route (edge); (2) safe operation of the application; (3) end-to-end optimal power consumption in the access, edge, and core networks; (4) security of the network; and (5) reliability of the network.

This requires multiple algorithms – AI, non-AI, or hybrid – to work together, including, e.g., (a) end-to-end route optimization; (b) teleoperating driving data analytics; (c) multi-domain energy consumption data analytics; (d) control and optimization of infrastructure power consumption; (e) access selection (terrestrial vs. non-terrestrial); (f) coverage optimization; (g) scaling of computing resources; (h) federated and secured data monitoring; (i) network security; and (j) reliability. These algorithms should be deployed at the network orchestrator and controller level to efficiently manage radio/network resources, in domains such as radio access and transport networks – C-band Radio Access Networks (RANs), subTHz/mmWave RANs and Non-Terrestrial Networks (NTNs) such as Unmanned Aerial Vehicles (UAVs) and Low Earth Orbit (LEO) satellites as a backbone – and computing resources at the edge and in cloud/core domains (e.g., physical and virtualized servers or container clusters).

III. DEMONSTRATOR DESIGN

6G-TWIN sets out to demonstrate the benefits of the proposed system in two stages:

First, *2D network planning*: This scenario will reproduce the vision as described above in its simplest form, i.e., where an operator wants to anticipate the capacities and status of edge nodes placed along the route to be taken, in order to guarantee connectivity for teleoperation and a high Quality of Service (QoS) information exchange. For this scenario, a real mobile platform will be teleoperated in a lab environment and will interact via Open RAN (O-RAN) connectivity with an emulated network core, providing openness support to the 6G infrastructure with an intelligent framework hosting Machine Learning (ML) based applications. These *xApps* will employ the NDT to examine trade-offs of various optimization opportunities balancing, e.g., power consumption versus requirements of safe teleoperated driving. These optimizations can then be realized to improve the perceived performance of the real mobile platform as it moves through the lab environment.

Second, *3D network planning*: This scenario is an extension of the previous one, considering additional units to the roadside edge nodes, notably by adding more vehicles as well as aerial and/or non-terrestrial nodes so as to have alternative or temporary access and computing units to guarantee the requirements of the use case. Specifically, UAVs and LEO [7] satellites will be considered. They could be used, for instance, to replace one or more of the edge nodes available in the event that their availability or capacity is not guaranteed. Multiple teleoperated vehicles will be introduced so that the capacity of the available computing nodes is challenged. To demonstrate this complex scenario, the real testbed used for the first scenario will be replaced by a pure simulation environment.

We will drive machine learning through a graph-based approach in order to better identify and organize the features. For instance, we propose using efficient and scalable data processing using Knowledge Distillation (KD) by capturing and *distilling* knowledge in a complex model and transferring it to a smaller model. This is because ML models have become larger and significant challenges have arisen regarding their deployment, especially on edge devices with limited resources. We also propose using self-supervised learning to design a zero-touch management framework that allows the network to self-manage and self-optimize, reducing the need for human intervention and minimizing the risk of human error.

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