This is the authors' accepted version of the article. The final version published by IEEE is C. M. Lentisco, C. Campolo, A. Molinaro, J. Martín-Pérez and L. Bellido, "Digital Twin-Assisted Radio Resource Allocation for Tele-Operated Driving," 20th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Paris, France, 2024, pp. 667-670, doi: 10.1109/WiMob61911.2024.10770471.

Digital Twin-assisted Radio Resource Allocation for Tele-operated Driving

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***Abstract*—Tele-operated Driving (ToD) is an ambitious use case in the automotive sector that enables the remote operation of vehicles, e.g., when they are located in dangerous environments, for logistics fleet operations. ToD heavily relies on 5G connectivity able to guarantee strict latency, reliability, and bandwidth requirements, for instance through a dedicated network slice. In this paper, we propose a Digital Twin (DT)-assisted radio resource allocation scheme that manages the Radio Access Network (RAN) resources within the ToD network slice. In particular, our contributions leverage interactions between the DT of the RAN and of other ToD players to feed an algorithm for efficient radio resource allocation, based on the actual ToD service demand on the planned driving paths. Early results on a realistic map demonstrate the resource savings achieved by our proposal compared to a static resource allocation scheme.**

***Index Terms*—Remotely guided vehicles, Resource management, 5G mobile communication, Digital twins, Network slicing.**

I. INTRODUCTION

THE 5G network has been defined to support a wide variety of innovative services, among which Tele-operated Driving (ToD) enables the operation of vehicles from remote control centers. ToD requires ultra-reliable, low-latency 5G communications during the entire vehicle's journey, with significant bandwidth demands that challenge ToD commercial deployment on a large-scale. According to the Third Generation Partnership Project (3GPP) [1], service latency should be limited to 5 ms, with a reliability of 99.999%. Additionally, each ToD-vehicle would typically consume 25 Mbps for sensor data transmission in the uplink and 1 Mbps for driving instructions in the downlink.

Network slicing has been designed within 5G to offer content and service providers isolated networks with specific Quality of Service (QoS) levels. The need of a dedicated slice for automotive applications has been recognized by 3GPP in [2] and specifically for a ToD service in [3]. Current research mainly describes mechanisms allowing multiple slices to share Radio Access Network (RAN) resources in an efficient manner, but resource allocation *within a slice* has received less attention. In [4], the authors propose a solution for adapting resource allocation in slices according to service demand; however, they do not analyze the specific resource needs for ToD. Novel slicing mechanisms are needed to address the challenging ToD requirements, by leveraging an accurate knowledge of the road topology and network capabilities and by *jointly* acting on route planning and resource allocation. Indeed, a ToD-vehicle may need to stop if the remote driver cannot navigate the vehicle efficiently and safely due to poor network conditions [5].

In this work, we propose to leverage the concepts of Digital Twin (DT) and Network Digital Twin (NDT) to the purpose of creating a collaborative ecosystem of road operators, ToD service providers and network operators to make ToD fleet management and resource allocation more efficient.

In [6] a DT creates accurate models of the road environment by interacting with the vehicle's perception system, with the twofold aim of improving the operator's telepresence and reducing the needs for network bandwidth to deliver data retrieved from on-board sensors. The NDT of a RAN collecting real-time information from paired network entities, such as gNodeB (gNB), and interacting with other DTs, can build dynamic network models for improved diagnosis and prediction purposes [7], [8].

To the best of our knowledge, the use of NDTs to support resource allocation mechanisms for ToD is almost unexplored. In order to fill this gap, in this paper, we provide the following main original contributions:

- We design a reference architecture, aligned with the Internet Research Task Force (IRTF) specifications [9], for the deployment of NDTs supporting ToD services.
- We exploit the interactions between NDT and DT of other providers (e.g., road operator, ToD fleet operator) to improve the radio resource allocation for the ToD service.
- We provide an algorithm to be deployed by the NDT for determining in advance and dynamically the amount of radio resources needed for a ToD slice *at each gNB* over the selected routing path, once the actual resource demands from the fleet of ToD vehicles are known.
- We collect (early) results in a realistic map, in terms of radio resources utilization, providing guidelines for future deployments.

The remainder of the paper is organized as follows. Section II describes the reference architecture leveraging DTs and NDTs, detailing the interactions among them and the proposed radio resource allocation algorithm for ToD. Section III presents the experimental results, and Section IV summarizes the conclusions and future steps of this work.

II. OUR PROPOSAL

Scenario and main players. The target of our study is the effective management of a fleet of remotely-driven vehicles with the support of the 5G network infrastructure, by leveraging cooperation among the ToD fleet manager, the network provider, and the road operator. ToD-vehicles need to travel in a given area, typically from a few origins, e.g., the fleet company's vehicle depots, towards multiple destinations, for instance for logistics delivery. A DT is coupled to the ToD operator, which tracks the trips to be performed by its vehicles' fleets. Origins of the trip as well as destinations are known in advance to the ToD DT.

The ToD service requirements should be met throughout the entire path, which may entail the crossing of multiple gNBs. We assume that the 5G network operator leverages a slice dedicated to the ToD service [2], [3]. Our focus is on the radio segment only, being the most challenging one, although the slice covers end-to-end resources assignment. The 5G network operator also has NDTs managing the different network segments and components. In particular, a RAN NDT handles a set of gNBs. A road operator manages DTs collecting relevant data from given areas of interest, e.g., information on road geometry, traffic status.

The reference architecture. Fig. 1 depicts the RAN NDT architecture, we conceived aligned with the IRTF documents, and specifically with the RAN instantiation in [7]. The core of the NDT is represented by the *Service Mapping Models*, which provide different models for representing the various RAN elements and functionalities. They can be analytical models, simulators, or Machine Learning (ML)-based models.

At the bottom, the *Basic Models* enable to capture the RAN configuration and the environment information, as retrieved to the so-called *southbound* and *sidebound interfaces*, respectively. In particular, the *Scenario topology* model provides the topographic information of the RAN area, such as detailed maps including buildings, streets, etc., built by the NDT by interacting with the Road DT through the *sidebound interface*. The *gNBs model* emulates the behaviour of the gNBs considering, among others, its position, operating frequency, bandwidth configurations, numerologies. The *Channel model* characterizes the radio links, considering the effect of propagation loss, interference and noise.

The *Functional models* are responsible for network analysis, emulation, diagnosis, prediction and assurance. Here, we focus on Radio Resource Management (RRM) policies for ToD, i.e., admission control and resource allocation, deployed according to the analytical Tele-operated Vehicle Admission Control and Routing (TOVAC) scheme in [10]. Thanks to these functions, when a ToD-vehicle requests a route, through the ToD DT, the RAN NDT is in charge of *(i)* planning the routing path that each ToD-vehicle should follow to experience the required QoS levels throughout the entire journey, as well as *(ii)* allocating the amount of radio resources needed at each gNB along the traversed paths. The constrained shortest routing path is selected for each ToD-vehicle by TOVAC. If sufficient radio resources are not available, a ToD-vehicle is denied, in order to prevent its trip to be unsafe.

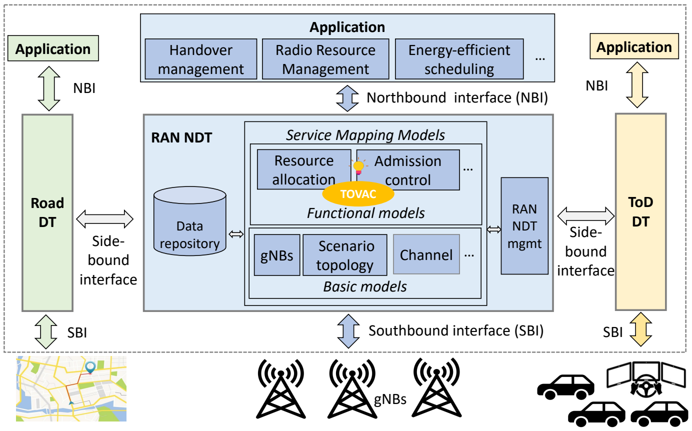

Fig. 1. The reference architecture.

Resource allocation algorithm in the NDT. Algorithm 1 details all steps of our proposed resource allocation scheme. An explanation of the algorithm is provided below.

The RAN NDT pre-builds a capacity graph G, whose edges $e \in E(G)$ are roads, each of them capturing the maximum number of ToD vehicles, $\nu_e^{\max}$, that each road can accommodate to meet the ToD requirements [10]. To compute $\nu_e^{\max}$: (i) the location of each radio cell r is obtained from the *Scenario topology model* in the RAN NDT; (ii) the Signal to Interference plus Noise Ratio (SINR) provided by every cell r at each road is computed using *Channel model* in the RAN NDT [10, (8)]; and (iii) algorithm in [10, (10)] is used to compute $\nu_e^{\max}$ for any road segment $E(r) \subset E(G)$. The resulting capacity graph G heavily depends on RAN parameters such as: the percentage of resources allocated to the ToD slice (σ_{ToD}^{max}), numerology (μ), frequency reuse factor (FRF), signaling overhead (OH), path loss (α), decoding error (ϵ_r) and transmission power (P). These parameters, detailed in Table I, are set in the experiments based on common values found in the literature.

The RAN NDT interacts with the ToD DT, through the *sidebound interface*, to obtain the set of sources $\{s_\nu\}_\nu \subset V(G)$ and destinations $\{d_\nu\}_\nu \subset V(G)$ of the trips that the ToD-vehicles in the fleet must take. Given the capacity graph and the set of sources and destinations, TOVAC executes a route planning algorithm to obtain the route $\mathcal{P}_\nu \subset E(G)$ taken by each vehicle. This route planning algorithm, which is a modified version of a classical A^* algorithm, incorporates an admission control mechanism [10, (12)] to prevent RAN congestion by limiting vehicle access. This approach ensures that the ToD service requirements are consistently satisfied for all vehicles in transit. That is, $|\nu : e \in \mathcal{P}_\nu \wedge t \in \tau_{\nu,e}| \le \nu_e^{\max}, \forall t, e \in E(G)$ with $\tau_{\nu,e}$ being the time interval at which vehicle ν crossed road e. Then, by analyzing the routes selected by TOVAC, the ToD service demand in each road section e is measured as the maximum number of vehicles that would be simultaneously

Algorithm 1 DT-assisted Radio Resource Allocation

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Create capacity graph $G$ and $\nu_e^{\max}, \forall e \in E(G)$
$\{\mathcal{P}_\nu\}_\nu \leftarrow$ TOVAC$(G, \{s_\nu\}_\nu, \{d_\nu\}_\nu)$   ▷ ToD routing & admission control
for $e \in E(G)$ do
    $\sigma_e^{\min} = \arg\min_\sigma \{|\nu : e \in \mathcal{P}_\nu \wedge t \in \tau_{\nu,e}| \leq \nu_e^{\max}(\sigma)\}$
    $\sigma_r \leftarrow \sigma_e^{\min}$   ▷ Allocate minimum RB percentage
end for
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accessing that section at any given time. Note that the TOVAC admission control mechanism ensures that this number remains within the maximum allowed limit ν_e^{max}. Finally, the resource allocation algorithm determines the minimum percentage of RAN Resource Blocks (RBs) (σ_e^{min}) necessary to accommodate the ToD demand for each road section. Specifically, for each road section e, we set σ_e^{min} as:

$$\sigma_e^{\min} = \arg\min_\sigma \{|\nu : e \in \mathcal{P}_\nu \wedge t \in \tau_{\nu,e}| \leq \nu_e^{\max}(\sigma)\} \qquad (1)$$

with $\nu_e^{\max}(\sigma)$ the maximum number of ToD vehicles that can traverse road e under a resource allocation of σ. The ToD demand in the road section e is defined as $|\nu : e \in \mathcal{P}_\nu \wedge t \in \tau_{\nu,e}|$.

III. PERFORMANCE EVALUATION

Instead of allocating a fixed (maximum) amount of resources to the ToD slice and hence, to each gNB of the RAN, as in [10], this paper explores the idea of dynamically slicing the RAN to meet the actual ToD service demand. To this aim, we have modified TOVAC, which is written in Python, by extending its functionality to run the NDT radio resource allocation algorithm described in Section II. Using the Torino city map, obtained using OpenStreetMap, and a map with the gNBs deployed in Torino, obtained using OpenCelliD, we conducted an experimental campaign that demonstrates that slicing the RAN network with the help of (N)DTs can be beneficial for managing the available resources more efficiently.

A. Main settings

Evaluation settings are summarized in Table I; further details can be found in [10]. We analyzed scenarios where the ToD provider requests 25%, 50%, and 100% of the RAN resources from the network. Experiments were performed for various fleet sizes (expressed as the number of trips in Table I) and different types of trips, with different combinations of origins and destinations.

B. Results

Fig. 2 illustrates the resource allocation needed (σ_e^{min}) on each road segment over the considered map for a limit case: a fleet of 101 vehicles *traveling from the same origin to the same destination*. First of all, it can be observed that many gNBs in the city, those covering road segments where ToD-vehicles are not expected to travel, do not need to reserve radio resources to meet the demand of this scenario. The TOVAC route planning algorithm finds two alternative routes from the origin to the destination for different ToD-vehicles (two different sub-paths are shown in the Figure). When it detects a network bottleneck in the shortest path between the origin and destination, it attempts to route additional vehicles from the fleet using a longer alternative route. TOVAC also performs admission control, resulting in some vehicles being denied network access, and hence stopped, as it will be explained later. In some of the road segments, it is necessary to reserve more resources than in others to admit the same number of vehicles. This depends on several factors, such as the distance of a vehicle crossing a road section to the serving base station. This further confirms the need of a dynamic, *per gNB,* resource allocation instead of a blind one.

TABLE I
SYSTEM PARAMETERS

ToD Parameters	
Parameter (Symbol)	**Value**
Service bitrate (b)	25 Mbps [1]
ToD Resource Allocation (σ_{ToD}^{max})	[25, 50, 100]%
Packet Delay Budget (PDB)	5 ms [1]
Number of origins ($N_{src} = \|\{s_v\}_v\|$)	1, 6, 11
Number of destinations ($N_{dst} = \|\{d_v\}_v\|$)	1, 11
Number of trips (N_{trips})	71, 101
Map size	50 km^2
RAN Parameters	
Parameter (Symbol)	**Value**
Numerology (μ)	2
Frequency (FR2)	26 GHz [11]
Frequency Reuse Factor (FRF)	3
Overhead (OH)	0.14 [12]
Pathloss exp. (α)	4 [13]
Decode (ϵ_r)	10^{-5} [14]
Vehicle transmission power (P)	23 dBm [15]
Bandwidth (B)	$[80, 320]$ MHz [11]
gNB density	108 gNB/km^2

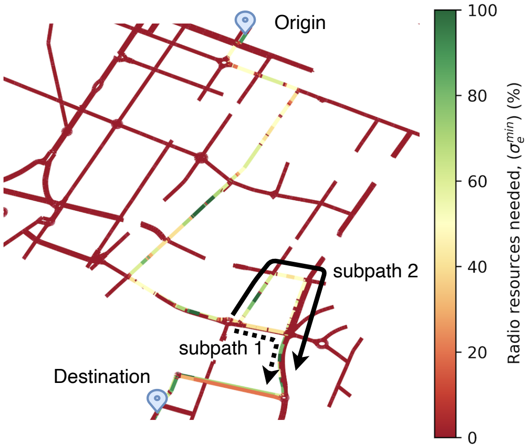

Fig. 2. Radio resources needed per gNB (σ_e^{min}), with $N_{SRC} = 1$, $N_{DST} = 1$, $N_{trips} = 101$, and $\sigma_{ToD}^{max} = 100\%$. The area of the map where the route is defined is illustrated.

Fig. 3a) shows the percentage of vehicles denied by the TOVAC admission control for fleets of different sizes (71, 101) traveling from a few origins ($N_{src} = \{6, 11\}$) towards multiple destinations ($N_{dst} = 11$). These values have been set to represent a possible logistics scenario for a fleet of delivery vehicles. The Figure indicates that the percentage of vehicles denied increases with the fleet size for a fixed σ_{ToD}^{max}. For instance, with σ_{ToD}^{max} set to 50%, 2.5% of a fleet of 71 ToD-vehicles were denied from driving. This percentage increases to 15% for a fleet size of 101 vehicles. On the other hand, the Figure shows how increasing

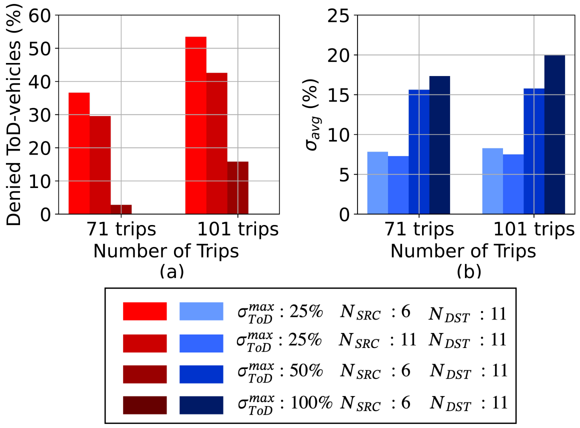

Fig. 3. Percentage of denied ToD-vehicles (a) and Average radio resources utilization (σ_{avg}) (b) for different combinations of σ_{ToD}^{max}, N_{SRC}, N_{DST}, and N_{trips}.

the number of sources (N_{src}) affects the vehicle denial rates. For σ_{ToD}^{max} equal to 25%, the percentage of denied vehicles decreases when the number of sources (N_{dst}) increases from 6 to 11. This is because trips are better distributed across the city map, resulting in less congestion around the origins. A special case occurs when σ_{ToD}^{max} is 100%, where the percentage of vehicles denied is very low.

Correspondingly, Fig. 3b), drawn for the same set of experiments, and reporting the average radio resources utilization (σ_{avg}) for all active gNBs, i.e., only serving base stations that are reserving resources for the ToD service, shows that the metric does not reach its maximum when σ_{ToD}^{max} is equal to 100%. This suggests that the network could accommodate larger fleets of vehicles for this value of σ_{ToD}^{max}. As a side effect, this setting results in an overprovisioning of resources, that could impact other services. Reasonably, larger vehicles fleets consume more resources than smaller fleets, but only when resources are available not do deny vehicles. For instance, with a σ_{ToD}^{max} equal to 100%, radio resources utilization is 17.2% for a fleet of 71 vehicles, and 20% percent for a fleet of 101 vehicles. This is not happening when σ_{ToD}^{max} is equal to 25%, where TOVAC is denying the ToD.

An important clarification is why radio resources utilization never reaches the maximum in any scenario. This is due to the TOVAC admission control mechanism. During simulations, all ToD-vehicles request routes simultaneously, leading to network congestion occurring around the origins as more trips are generated. Fig. 2 also illustrated this problem, showing that there are bottlenecks in the path from the origin to the destination that prevent some base stations from being fully utilized.

IV. CONCLUSION

This paper proposes a DT-assisted radio resource allocation scheme that dynamically slices the RAN based on the ToD service demand. Preliminary results indicate that leveraging the capabilities of DTs and network slicing enables a more judicious allocation of resources. In particular, by coupling route planning and admission control, the proposed NDT algorithm can achieve a good balance between network efficiency and the effective remote operation of vehicles.

This work paves the way for better specifying the sidebound interfaces among (N)DTs for configuring network slices to meet the specific requirements of ToD service providers. Moreover, to increase the number of admitted ToD-vehicles by more efficiently allocating resources, a possible future step is to combine TOVAC with adaptive streaming technologies and improved road perception as well as mechanisms that dynamically adjust the speed of the ToD-vehicles to reduce the bandwidth demand. Prioritization of the most urgent trips could be also implemented to serve the same purpose.

ACKNOWLEDGMENTS

This work was partially supported by the Remote Driver project (TSI-065100-2022-003) funded by Spanish Ministry of Economic Affairs and Digital Transformation and partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART").

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