NG-TCN: Towards Network Slicing in on-board Wireless Train communication networks

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1. Introduction

The Train Communication Network (TCN) is the typical wired on-board network of the train defined by the standard IEC 61375 [1]. The TCN architecture is structured hierarchically with two main levels: the Train Backbone Network (TBN) and the Consist Network (CN) shown in figure 1. The TBN facilitates inter-consist communications, enabling communication between different train units. In contrast, the CN supports intra-consist communication, connecting carriages that are inseparable during operation. The existing TCN infrastructure relies on a costly and maintenance-intensive wired system, highlighting the necessity for advanced wireless technologies and network virtualization to enhance efficiency and flexibility.

Therefore, European projects have advocated for the Next generation of TCN (NG-TCN) including a Wireless Train Backbone Network (WLTBN). Nevertheless, Railways Communications services are complex in the diversity of requirement as specified by the future railways communication User requirement specification by the UIC [2]. This complexity includes priority of service, security, reliability, throughput which could be amplified in a wireless context therefore posing a traffic orchestration problem [3]. Despite significant efforts made at the European level to explore wireless technologies that could meet the railways communication requirements, deeper investigations are needed to address the resource orchestration question in this wireless approach.

To deal with that, the advent of 5G is regarded as promising in the railway context [4]. Network slicing (NS), which allows the segmentation of a single network into different virtual networks on the same infrastructure, is a 5G feature with great potentials in this case. Despite this interesting potential, there is very limited research works focusing on network slicing within the WLTBN. This paper describes the wireless train backbone problem and explores how Network Slicing principles can be leveraged to enhance WLTBN. We review related works to contextualize current research and identify gaps. We also highlight the main challenges and research directions in this field, including spectral efficiency, intelligent resource management, and service reliability.

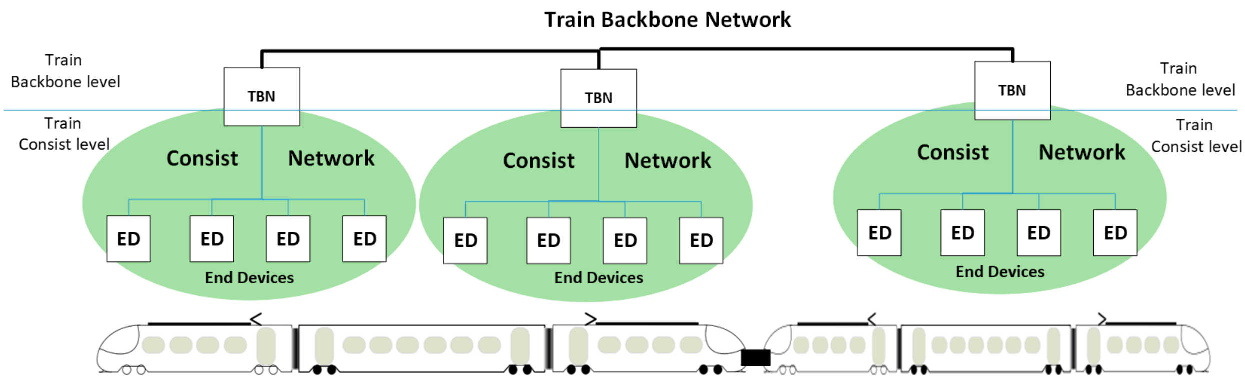

Figure 1: Wired TCN Architecture

2. Why Network slicing is a Key Enabler in WLTBN

2.1. The Wireless Train Backbone Problem

The introduction of wireless technologies at both the backbone and consist levels aims to create solutions that increase flexibility, ease interoperability, and reduce the costs associated with wired solutions [3]. The WLTB is designed to connect different consists, or groups of vehicles, within a train as proposed by Roll2Rail project [5] shown in figure 2. Unlike a wired network, introducing wireless technology into the train backbone network brings inherent challenges, notably sensitivity to radio conditions such as signal propagation, interference, and loss. WLTBN serves multiple onboard end devices with diverse service requirements varying in priority, latency, and throughput. It is important to maintain the coexistence of heterogeneous requirements, which span sensitive data traffic, video streaming, voice communication, and low-latency periodic data. All train functions collected in CENELEC EN15380-4 standard are categorized into three key domains: Train Control and Management System (TCMS), Operator Oriented Services (OOS), and Customer Oriented Services (COS). TCMS consists of onboard systems like propulsion and braking, requiring reliability, high security level and minimal latency. OOS supports operational services for scheduling and maintenance with throughput requirement performance like CCTV and Passenger information System (PIS). COS enhances passenger experience with real-time information and entertainment, demanding high bandwidth and seamless connectivity. Addressing these complexities is essential to maintain operational efficiency and passenger satisfaction on trains.

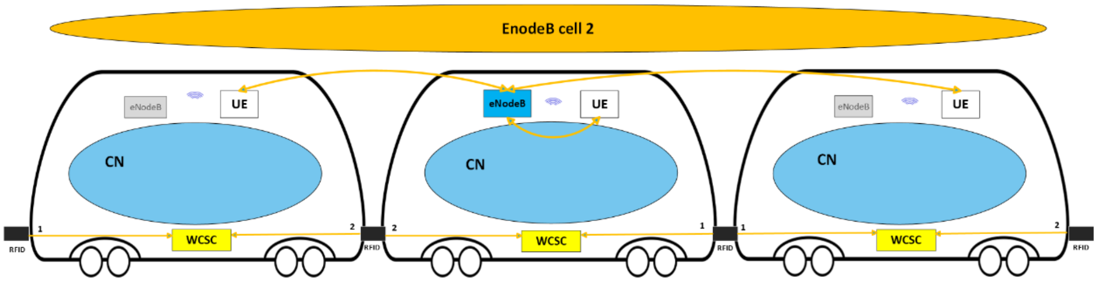

Figure 2: NG-TCN with wireless Train backbone Network using 4/5G

2.2. The Network Slicing Principle

Network slicing, a core feature developed in the 5G 3GPP standards since release 15 [6], involves partitioning network resources to create virtual, customizable networks for various services or user groups. This approach extends cellular networks beyond the traditional "individual mobile user" model to support new applications with diverse requirements [7]. By forming logical "network slices," multiple independent end-to-end (E2E) networks can coexist on the same physical infrastructure. Each slice is tailored by the network operators to meet service requirements sensitive to performance metrics such as latency for Ultra-Reliable Low-Latency Communications (URLLC), throughput for Mobile Broadband (MBB), and reliability for Vehicle-to-Vehicle (V2V) or critical railway communications.

2.3. Leveraging NS in WLTBN

5G-based Network Slicing is considered key for future railways operations [8]. Considering the varieties of service embedded on-bord the train, NS can be leveraged as an enabling factor for optimal resource utilization. Considering the above domains TCMS, OSS and COS, three dedicated Network slice can be allocated tailored to their specific needs namely Critical, performance and business slice. The TCMS, categorized under “critical” Slice use cases, requires ultra-reliable low-latency communication (URLLC) for real-time monitoring and control of onboard systems. The OOS can come under the "Performance" slice use cases, where network slices are designed to optimize throughput and efficiency, supporting applications such as in-train communication between staff and passengers. The "Business" slice use cases can be dedicated to COS prioritizing high bandwidth services for passenger. Another crucial aspect of network slicing for safety-critical rail applications is cybersecurity [9] . Using network slicing, various types of applications, such as low-latency remote driving applications and platooning applications, may be supported at the same time despite their different virtual network characteristics – e.g., different frequency bands, heterogeneous throughput requirements, different latency tolerances, and heterogeneous security requirements [10].

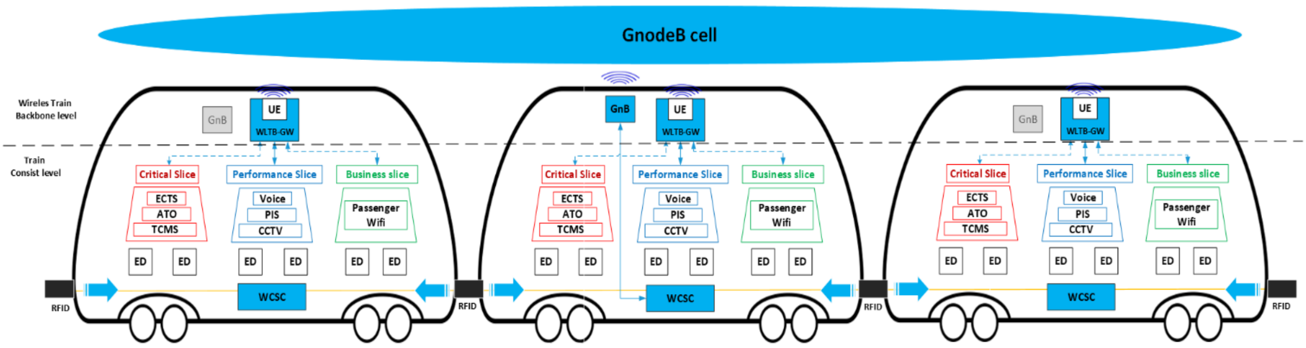

Figure 3: 5G Network Slicing in wireless Train backbone Network

3. Related Works

European projects have significantly advanced the Wireless Train Backbone Network (WLTBN) in the NG-TCN context. The Roll2Rail project (2015-2017) specified the requirements for the NG-TCN system, addressing both the Wireless Consist Network (WLCN) and WLTBN levels. It implemented one ENodeB per train consist with UEs as Access Points for end devices, and utilized RFID for train topology discovery as shown in figure 2. SAFE4RAIL 1 and 2 (2019-2022) developed a WLTBN prototype based on LTE-V2X with additional modules for service discovery and mesh networking, and investigated NR-V2X. CONNECTA 1, 2, and 3 (2016-2023) concluded that no existing radio technology fully satisfies the Train Control and Management System (TCMS), and suggested combination of LTE-V2X and LTE-D2D functionalities for WLTBN.

IAM4RAIL project (ongoing) found Wi-Fi suitable for data rates but not for TCMS due to its non-deterministic access behavior, and plans to study NR-V2X for NG-TCN requirements. A solution based on 5G-NR and a combination of technologies is studied in the framework of the project by SNCF [11]._These projects collectively enhance wireless train communications by addressing key challenges and proposing innovative solutions. But the question of Network slicing in NG-TCN has not received enough attention.

Authors in [12] proposed Slicing model to enable coexistence of train control services (TCS) and passenger information services (PIS). Considering slice attributes such as the number of terminals, latency for TCS, and throughput for PIS, channels are reserved for slices in advance. Authors considered a simplified service requirement assuming two types of services, while railway requirements have more varying characteristics as explained in Section 2.

4. Challenges and Research Directions

4.1. Spectral Efficiency

Spectral efficiency remains a challenge due to the need for a harmonized railways bands across Europe and the limited availability of free bands comparable to those currently allocated for 5G Public MNOs, where network slicing is widely studied. Consequently, there is a need to adapt resource allocation in the Radio Access Network (RAN) for future railway mobile radio[13]. The Future research should focus on advanced modulation and coding schemes, spectrum sharing techniques, and dynamic spectrum access methods to improve spectral efficiency. Additionally, exploring the use of higher frequency bands (millimeter wave) and integrating multiple-input multiple-output (4x4 MIMO) technology as suggested in [14], could further enhance data throughput. The implementation of Reconfigurable Intelligent Surfaces (RIS) on the train explored in [15] can be considered as intelligent mirrors along with beamforming techniques to direct signals more efficiently, thereby significantly improving spectral efficiency and coverage [16].

4.2. Intelligent Resource Management

Managing resources in a dynamic train environment is highly complex because it involves various interdependent variables and constraints. With NS these interdependencies can quickly result in a combinatorial explosion of possible solutions, categorizing the problem as NP-hard. In computational complexity theory, NP-hard problems are those for which no polynomial-time algorithm is known to exist that can solve all instances optimally. This complexity underscores the need for sophisticated algorithms to handle resource orchestration. As surveyed in [17], Machine learning, particularly Deep Reinforcement Learning (DRL) in [18], offers promising solutions with the potential to predict network conditions [19], optimize resource allocation [20], and ensure quality of service (QoS) for various applications [21]. Future research should investigate the development of ML-based algorithms for real-time resource management, adaptive network slicing, and predictive maintenance.

4.3. Service Reliability

Ensuring uninterrupted service delivery, even during events like train carriage (consist network) coupling, is critical for the WLTBN. Particular attention should be drawn on redundancy mechanisms, fault-tolerant network designs, and robust handover protocols to maintain continuous service. Leveraging edge computing for local data processing can enhance reliability by reducing dependency on central servers, thereby minimizing latency, and improving the responsiveness of on-board systems for real-time applications and critical operations. Authors in [22] showed the benefits of on-board content caching in optimizing content retrieval. Additionally, implementing stringent security measures is crucial to protect against cyber threats and maintain service integrity.

5. Conclusion

In this paper we explored the potential of leveraging 5G Network Slicing to enhance the Wireless Train Backbone Network (WLTBN). The current limitations of the Train Communication Network (TCN), including high costs, maintenance challenges, and inflexibility, made the need for advanced wireless technologies and network virtualization becomes evident. The transition to WLTBN presents inherent challenges, particularly sensitivity to radio conditions such as signal propagation, interference, and attenuation. These points are analyzed within the IAM4RAIL project as mentioned previously. The traffic orchestration problem arises from the complexity involving service prioritization, security, reliability, and throughput, which can be amplified in a wireless context. Network slicing with 5G offers promising potential to ensure the coexistence of complex and heterogeneous service requirements, catering to diverse communication requirements and ensuring high performance for various train subsystems. Designing intelligent, relevant, and secure slice orchestration algorithms is crucial for leveraging network slicing in the context of railways. Key challenges identified include spectral efficiency, intelligent resource management, and service reliability. Future research should investigate these areas for seamless integration of wireless technologies in railways, enhancing passenger and freight services and paving the way for innovative railway operations.

6. Disclaimer

The views and opinions expressed in this paper are those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union projects mentioned here, nor the granting authorities can be held responsible for them.

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