Research Demand and Review on Deterministic Communication in Hybrid 5G networks based on TSN

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***Abstract*—Time-Sensitive Networking (TSN) has emerged as a fundamental component in the communication infrastructure of Industry 4.0, primarily due to its ability to provide deterministic and ultra-reliable communication. These features are critically important for applications generating real-time traffic, which require precise timing and minimal latency. TSN, encompassing a set of IEEE 802.1 standards, is engineered to establish a reliable and deterministic communication framework over Ethernet. However, the need for flexibility and cost-effective infrastructure has driven the adoption of wireless communication, which offers a complementary set of advantages. Consequently, hybrid networks that integrate wired TSN with wireless technologies are becoming increasingly prevalent. Nevertheless, the integration of these heterogeneous systems poses significant challenges, particularly due to the differing characteristics of TSN protocols and wireless networks, such as 5G. Wireless networks are prone to issues like congestion and jitter, which can lead to increased packet loss and delays, compromising the ability to meet strict time constraints. This paper explores the integration of TSN with 5G networks, focusing on research gaps towards achieving deterministic communication and ensuring timely packet delivery through the synchronization of network elements and the strategic scheduling of packets based on pre-allocated resources within the 5G network.**

I. Introduction

Ultra-Reliable Low Latency Communication (URLLC) is one of the most critical services offered by 5G networks, characterized by stringent QoS requirements that prioritize low latency and high reliability. The implementation of URLLC in 5G involves a sophisticated scheduling mechanism managed by the Radio Resource Controller (RRC) [1]. The RRC processes admission control, evaluating and prioritizing scheduling requests according to the QoS demands of various traffic types. The Medium Access Control (MAC) scheduler, acting upon the directives of the RRC, dynamically allocates resources to meet these demands. In particular, URLLC frames are given the highest priority, necessitating their immediate scheduling and transmission with minimal latency. This is facilitated through mechanisms such as mini-slot scheduling, which allows for the rapid transmission of URLLC packets, and pre-emption, where ongoing transmissions of lower-priority data can be interrupted to accommodate URLLC traffic. Despite these capabilities, the dynamic nature of 5G scheduling can introduce variability in latency, which is incompatible with the deterministic requirements of certain industrial applications [2]. In contrast, TSN provides a deterministic communication model by leveraging precise time synchronization and the Time-Aware Shaper (TAS) scheduler. The TAS scheduler operates based on predefined schedules and priorities, ensuring that traffic is transmitted within specific time windows as dictated by the Gate Control Lists (GCLs). This deterministic approach is crucial for applications where predictable latency and timing are non-negotiable.

II. 5G-TSN Integration

The integration of 5G and TSN networks as illustrated in figure 1 has been a focal point of research and standardization efforts, particularly within the Third Generation Partnership Project (3GPP). The 3GPP has been developing mechanisms to incorporate TSN capabilities into the 5G system, treating it as a logical extension within the TSN domain. This integration is facilitated by the use of TSN Translators (TSN-TTs), which bridge the TSN and 5G domains. The system architecture includes Network-Side Translators (NW-TTs) and Device-Side Translators (DS-TTs), which serve as interfaces between the TSN infrastructure and the 5G network [3]. These translators are responsible for recording the residence time of data as it traverses the network, a critical factor in maintaining the accuracy of scheduling and synchronization. The Application Function Translator (AF-TT), which operates within the 5G control plane, plays a pivotal role in exposing the configuration and status of the 5G system to the Centralized Network Controller (CNC). The AF-TT provides detailed information about the network's resources, including port availability, component latency, and QoS profiles, it also provides Channel State Information (CSI) which provided by the connected UEs and transmitted as Channel Quality Indicator (CQI) which defines the state of the channel and transmission requirements to achieve a successful transmission. This data enables the CNC to make informed decisions about traffic scheduling, ensuring that TSN traffic is appropriately prioritized and routed through the network [4].

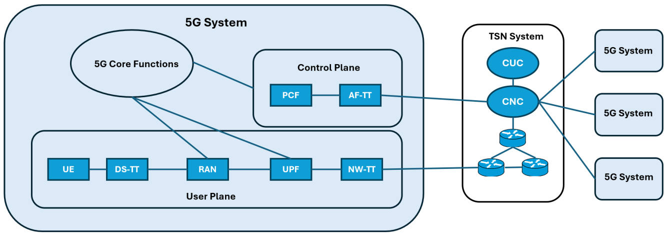

Fig. 1. 5G-TSN Integration Architecture

III. State-of-the-art

Recent research has been increasingly focused on developing scheduling algorithms to ensure deterministic communication. The authors in [5] explored the issue of scheduling misalignment between TSN traffic and the allocated resources in semi-persistent scheduling frameworks, attributing these discrepancies to signaling overhead and fluctuating channel conditions. The authors proposed a mechanism that dynamically adjusts resource allocation based on real-time channel conditions, which successfully reduced latency but fell short of achieving fully deterministic scheduling. Another advancing study in [6], [7] introduced a scheduling algorithm that allocates resources based on the periodicity of TSN traffic. This approach involves collecting detailed information about the departure and arrival times of TSN packets and their periodicity, and then scheduling resources accordingly. The authors claimed that this method ensures time-bound delivery and enhances the system's capacity to handle additional TSN traffic. However, the approach's reliance on traffic periodicity poses a limitation, as it may fail to provide deterministic communication under conditions of high traffic density or irregular traffic patterns.

Additionally, the research in [8] have explored the application of K-Means clustering and rough set theory to optimize the QoS mapping between TSN and 5G networks. They proposed the Adaptive Semi-Persistent Scheduling (ASPS) algorithm, which initially requests resource allocation based on QoS requirements and reserves these resources when available. In scenarios where reserved resources are insufficient, dynamic scheduling is employed upon the arrival of TSN traffic. However, this method raises concerns about the ability to maintain deterministic communication, as the reliance on dynamic scheduling may result in resource allocation failures during peak traffic periods, thereby undermining the timely delivery of TSN packets. Also, the authors in [9] managed to minimize the transmission delay by using the CSI received by UEs and employed CQI to optimize the scheduling mechanism to achieve less transmission delay. Moreover, they presented a machine learning mechanism which predicts the channel conditions to eliminate the cross network delay of delivering data and minimize end to end delay. The outcomes achieved less delays. However, deterministic communication requires pre-reserved resources to allocate a dedicated transmission path to destination.

IV. Research Gaps and Challenges

Despite notable advancements in the integration of 5G and Time-Sensitive Networking (TSN), several critical challenges remain unaddressed. Current systems have succeeded in achieving low latency; however, they fail to consistently provide deterministic communication within a fixed time bound. This shortfall arises from multiple factors, including inadequate precise time synchronization across all TSN bridges and the inherent variability introduced by dynamic scheduling mechanisms in 5G networks. The mapping of TSN scheduling parameters to the scheduling frameworks used in 5G adds another layer of complexity, often leading to timing discrepancies. Furthermore, the wireless nature of 5G networks exacerbates these challenges due to the unpredictable behavior of radio channels, which can result in fluctuating latency and jitter.

State-of-the-art research has primarily concentrated on optimizing the alignment between TSN domain schedulers and the 5G dynamic and Semi-Persistent Scheduler (SPS) to minimize latency. However, achieving latency in accordance with TSN standards requires dedicated resources that can guarantee deterministic communication. A pertinent question arises: How can 5G networks, designed with flexibility in mind, be adapted to support the stringent requirements of TSN traffic without compromising efficiency?

To address this gap, our research focuses on addressing the following points:

- implementing a robust admission control mechanism that continuously assesses the availability of resources across all logical networks connected to the TSN domain. This mechanism, aligned with pending QoS requirements, offers the TSN domain a detailed overview of network topology and component availability, facilitating informed resource allocation decisions.
- exploring the feasibility of allocating dedicated resources within the 5G infrastructure for TSN traffic. These dedicated resources would ensure that TSN traffic can achieve the required level of deterministic communication, while allowing these resources to be used by regular 5G traffic in the absence of TSN traffic, thus optimizing resource utilization.
- Design and implementation of TSN scheduling algorithm to maintain the connected logical networks such as the genetic algorithm as it was optimized in work of the authors in [10].
- we propose separating the scheduling responsibilities for TSN traffic from the general 5G schedulers. Specifically, the TSN domain would independently manage scheduling considering 5G wireless network behavior and conditions and then forward traffic for prioritized transmission within the 5G network. This approach necessitates the TSN domain's comprehensive understanding of all logical bridges and the global network topology, ensuring fault tolerance through spatial redundancy in line with IEEE 802.1cb standards.

- The proposed semi-scheduler needs to consider maintaining reliability by ensuring spatial redundancy utilizing IEEE802.1cb standards throughout the topology.

The semi-static scheduling model capitalizes on comprehensive information about network topology, including prereserved resources and timing details. This data is used to develop a schedule that guarantees both deterministic delivery and high reliability of TSN traffic. Furthermore, our approach enhances network reliability through spatial redundancy, allocating resources across multiple paths. This design ensures that even in the event of network failures, the system can maintain uninterrupted service, thereby meeting the rigorous demands of industrial applications.

V. Evaluation

The methodology of this work will be rigorously tested and simulated to obtain results that will be compared with existing dynamic scheduling systems and state-of-the-art published research as explored in section III, thereby supporting the proposed claims and mechanisms. To validate the proposed integration framework, the Omnet++ simulation environment will be utilized. This simulation will model a hybrid network that integrates a TSN domain with various logical bridges to emulate a comprehensive TSN network. The primary focus will be on hard real-time applications that generate deterministic traffic, which will be used to evaluate the effectiveness of the proposed scheduling mechanisms. The simulation environment will be enhanced using Inet 4.5 and Simu5G [11] libraries, which are specialized extensions of Omnet++ that provide robust support for TSN protocols and 5G core network functionalities, including Radio Access Network (RAN) components such as gNodeB.

Additionally, the performance and effectiveness of 5G-TSN scheduling will be evaluated using the OpenAirInterface (OAI) and OpenRAN frameworks. OpenAirInterface is an open-source software platform that emulates the full 3GPP stack for 5G, encompassing both core network and RAN components. This platform offers a flexible environment for testing and validating 5G network functionalities, making it suitable for assessing the integration of 5G with TSN. OpenRAN, another open-source initiative, supports the disaggregation of RAN components, enabling custom deployments and configurations, which is essential for testing advanced scheduling algorithms. By leveraging these platforms, the proposed scheduling algorithms will be subjected to rigorous evaluation under various network conditions, simulating real-world 5G-TSN deployments.

Within the TSN domain, the system will take into account all QoS requirements across the network topology to appropriately allocate resources. The proposed scheduler will specifically handle the scheduling of hard real-time traffic, ensuring that this traffic is accurately deployed across all connected logical bridges. The simulation's primary focus will be on evaluating the integrated TSN-5G network's performance, particularly concerning latency, reliability, and the precision of time synchronization. Key performance indicators (KPIs) will include metrics such as end-to-end latency, jitter, packet loss rates, and the efficiency of resource allocation strategies. By conducting a series of simulation scenarios, we will assess the effects of various network configurations and traffic patterns on the network's ability to meet stringent deterministic communication requirements.

VI. Conclusion

The integration of TSN and 5G represents a significant advancement in communication technologies, particularly for Industry 4.0 applications that demand both flexibility and determinism. While current implementations provide a foundation for low-latency communication, achieving true deterministic performance requires overcoming several technical challenges. This research proposes a novel framework for integrating TSN and 5G, leveraging semi- static scheduling to ensure deterministic packet delivery within strict time bounds. The proposed solution offers a comprehensive approach to managing the complexities of heterogeneous network integration, paving the way for reliable and predictable communication in critical industrial applications. Future work will focus on refining the simulation model, exploring additional optimization strategies, and conducting real-world validations to further demonstrate the viability and effectiveness of the proposed approach.

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