Work in Progress: A Centralized Configuration Model for TSN-5G Networks

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***Abstract*—The integration of Time-Sensitive Networks (TSN) with 5G cellular networks requires a defined architecture for network configuration and management. Although 3GPP specifications provide necessary means for the TSN-5G integration, the operation of such converged TSN-5G network remains an open challenge for the research community. To address this challenge, this paper presents the ongoing work in developing a centralized architectural model to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa. The proposed architectural model uses knowledge of the traffic characteristics to carry out a more accurate mapping of quality of service attributes between TSN and 5G.**

***Index Terms*—5G, Time-Sensitive Networking, TSN-5G, Network Configuration.**

I. Introduction

The advancement in the Industrial Internet of Things (IIoT) brings many advantages such as increase in productivity and safety in the industrial domains, decrease in the cost of infrastructure and production error rates, among others [1]. The IIoT employs numerous embedded IoT devices to increase automation, predict machine failures, monitor various components of the system, and ensure safe human-machine interaction [2]. These embedded IoT devices are often required to continuously communicate with each other as well as with the existing industrial infrastructure. In the case of timing predictable IIoT applications, the embedded devices require high-bandwidth, low-latency and timing predictable communication.

Ethernet is a promising communication technology to support high bandwidth wired communication. However, traditional Ethernet is unable to support low-latency and predictable communication. The IEEE 802.1 Time-Sensitive Networking (TSN) Task Group developed a set of standards for Ethernet to support the low-latency required by IIoT systems. Specifically, TSN standards provide low-latency, fault tolerance and online configuration capabilities to switched Ethernet communications[1]. For these reasons, TSN has become the most promising solution to build the communication infrastructures of novel industrial applications [3].

Another promising solution to meet the stringent low-latency communication of the industrial applications is the fifth generation of mobile network technology, i.e. 5G. This technology is capable of supporting the required levels of network latency with its Ultra-Reliable Low-Latency Communication (URLLC) service [4]. Furthermore, the Release 16 of 3rd generation partnership project (3GPP) [5] introduces the integration of TSN and 5G to ensure seamless operation of industrial automation devices. A converged TSN-5G network introduces a greater level of flexibility in the network communication, while meeting the requirements of high-bandwidth and low-latency communication.

Although 3GPP specifications provide the necessary means for the TSN-5G integration, the operation of such converged TSN-5G network in low-latency applications remains an open topic to the research community. Specifically, one of the key mechanisms to provide timing guarantees in TSN-5G networks is the mapping of TSN traffic to 5G. Currently, 3GPP proposes to map TSN traffic to 5G using priorities only. Nonetheless, this is not the most suitable approach to provide low-latency and bounded jitter. Instead, we propose to use a mapping technique that takes into account further traffic information, i.e. the bandwidth, packet loss rate, deadline and maximum acceptable jitter [6].

Currently, the 3GPP specification proposes to carry out the mapping of TSN traffic to 5G within the 5G devices. Nonetheless, if we want to take advantage of the benefits provided by a richer mapping approach we can no longer carry out the mapping within the devices. On the one hand, the mapping would be more complex and, thus, harder to carry out on-the-fly every time a TSN frame is received. On the other hand, providing the necessary information about the traffic to each 5G device would introduce additional overhead in the network.

For these reasons, in this work we propose to carry out the traffic mapping within the Centralized Network Configuration entity (CNC) devised in the IEEE Std 802.1Qcc [7] standard. The CNC is responsible for configuring the network devices in TSN. We propose to take advantage of its complete view of the network and its knowledge of the traffic to carry out the mapping of TSN-5G traffic. Once the mapping is carried out, the CNC will use the Network Configuration (NETCONF) protocol to configure both TSN and 5G bridges.

The remainder of the paper is structured as follows. Section II provides an overview of the most important TSN and 5G concepts, as well as the existing related work. Section III describes the design rationale of the proposed configuration architecture. Finally, Section IV concludes the paper by summarizing the most important contributions and pointing at future work directions.

II. Background and Related Work

In this Section we discuss the basic TSN and 5G concepts necessary to understand the rest of the paper, as well as the related work.

[1]https://1.ieee802.org/tsn/

A. Background

1) Time Sensitive Networking: TSN is a set of standards developed by the TSN Task Group to provide standard Ethernet with low-latency, fault tolerance and online configuration capabilities. Specifically, the IEEE Std 802.1Qcc [7] standard proposes centralized architectures to support the online configuration of TSN networks. Centralized architectures are proven to be more adequate to carry out complex configuration decisions in real-time [8]. For this reason, there is a growing interest in using TSN's centralized architectures to configure the networks of IIoT applications, which are expected to be large and mutable.

The IEEE Std 802.1Qcc standard introduces two centralized architectures, namely the Centralized Network/Distributed User, in which only the network is managed by a centralized entity while the application is managed in a distributed manner; and the Fully Centralized architecture, where all the devices in the system are managed centrally. Fig. 1 depicts the Fully Centralized architecture, which we selected to build our configuration architecture for TSN-5G networks.

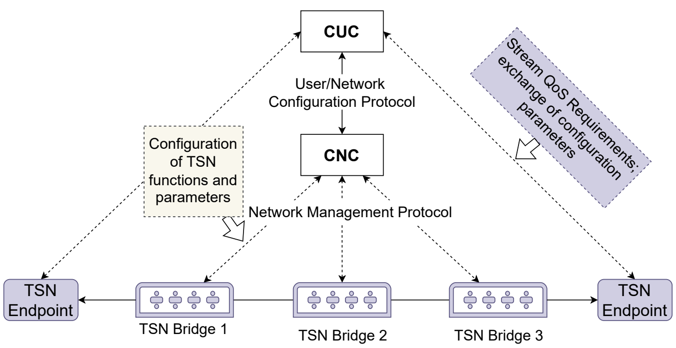

Fig. 1: Fully Centralized TSN Configuration Model.

The Figure depicts a TSN network with 3 bridges, 2 end stations, the so-called Centralized User Configuration entity (CUC) and Centralized Network Configuration entity (CNC). On the one hand, the CUC is responsible for gathering the application requirements, calculating new possible configurations and informing the CNC about how these requirements affect the network, e.g. creation of a new stream of information or elimination of existing ones. On the other hand, the CNC is responsible for monitoring the network, calculating new network configurations based on the information received from the CUC or the network itself, and deploying the configuration in the bridges.

The flow of information of this model is as follows:

- The end stations send their Quality of Service (QoS) requirements to the CUC entity, such as data rate, traffic class, priorities and worst-case latency.
- The CUC relays the end stations' requirements to the CNC entity.
- The TSN bridges send their capabilities to the CNC. These capabilities include bridge delays per port and class, propagation delays per port, and priorities.
- Since the CNC has an overview of the whole network, it calculates an adequate configuration for the network. This configuration may include the schedule of the time-triggered traffic, but also the configuration of mechanisms for the timely transmission of event-triggered traffic or for frame preemption.

2) 5G network: The fifth generation of mobile networks (5G) is designed to address six challenges that were not adequately addressed by the previous generations of mobile networks i.e. higher capacity, higher data rate, lower end to end latency, massive device connectivity, reduced cost and consistent Quality of Experience provisioning [9], [10].

The 3rd Generation Partnership Project (3GPP)[2] identifies Ultra-Reliable Low-Latency Communication (URLLC) as a key usage scenario of 5G. URLLC is applied for the event notification of critical applications with low-latency and reliability requirements, such as vehicular and industrial control applications [11]. The capabilities of URLLC makes 5G a suitable wireless candidate for time-sensitive communication achieving ultra-low latency down to 1 ms and reliability up to 99.9999% [12]. 5G key URLLC capabilities enable the integration of 5G mobile network with TSN wireline network providing converged deterministic connectivity for industrial automation.

B. Related Work

There are several existing works focusing on the integration model of TSN-5G network. In this section, we present an overview of the works that have been proposed in the literature.

Ginthör et al. [13] present a joint configuration approach that enables end to end scheduling optimization over a bridged TSN-5G network. The architectural model of the network consists of a converged network with several TSN bridges and 5G as a logical TSN bridge. The authors use the fully centralized network configuration model, which is suitable for end to end optimized schedules. Similarly, authors in [14], [15], [16] analyze the integration of TSN-5G considering 5G as a logical TSN bridge, while utilizing the centralized network configuration model. Such integration consists of 3 TSN translators (TT) used as an interface with a TSN network while achieving transparency of 5G system: (i) Device-side TSN translator (DS-TT) located at the User Equipment (UE), (ii) Network-side TSN translator (NW-TT) residing at the User Plane Function (UPF), and (iii) TSN Application Function (TSN AF) which is responsible for showing the 5G system capabilities to the CNC and then carries out the mapping of TSN traffic to 5G and manages the traffic forwarding.

In our work, we move the mapping functionality from the TSN AF to the CNC, as the CNC has the information needed to map TSN QoS requirements to 5G QoS profiles using more advanced mapping techniques [6]. To the best of our knowledge, this is the first proposed architecture that maps TSN traffic to 5G QoS profiles in a TSN CNC.

III. Proposed Architecture

A converged TSN-5G architecture requires translation functionalities to forward the traffic and different QoS-es from the wired to the wireless network and vice-versa.

[2]https://www.3gpp.org/about-3gpp

The 3GPP Release 16 [5] standardizes these translation functionalities into 3 parts: 1) DS-TT function, which resides on a UE side of 5G network, 2) NW-TT function, which resides in the UPF side (both on the user plane), and 3) TSN AF, which resides on the control plane and is used to influence traffic routing in the user plane based on QoS mapping of TSN QoS-es to QoS Identifiers or profiles specified in 3GPP Release 16 [5].

As we have discussed in Section I, the current 3GPP integration of 5G and TSN proposes to carry out the mapping of TSN traffic to 5G within the 5G systems. Furthermore, the mapping consists in a correspondence between TSN priorities and 5G QoS Identifiers. Unfortunately, this mapping technique does not allow to take advantage of the wide range of QoS Identifiers available in 5G. For this reason, we use a QoS mapping technique between TSN and 5G not only based on traffic classes of a TSN network, but using other QoS parameters such as deadline, jitter, bandwidth, and packet loss rate which allows to provide a higher granularity of the QoS.

In order to take advantage of the benefits brought by our mapping function we need to modify the configuration architecture. Specifically, we move the TSN AF functionality inside the CNC for a series of reasons. First, the CNC has the complete view of the network, which means it already has all the information required to perform the QoS mapping between TSN and 5G traffic. Second, since this mapping technique is more complex, it requires higher computation resources than those available in 5G systems. Third, performing the mapping in the CNC allows to perform it only once for the entire network, instead of having to execute it once in each 5G system. Finally, carrying the mapping out in the CNC prevents introducing additional bandwidth and timing overhead in the network, as the only information that must be transmitted is the result of the mapping, and not the entire traffic information. Fig. 2 depicts the proposed architecture, which we will explain in detail next.

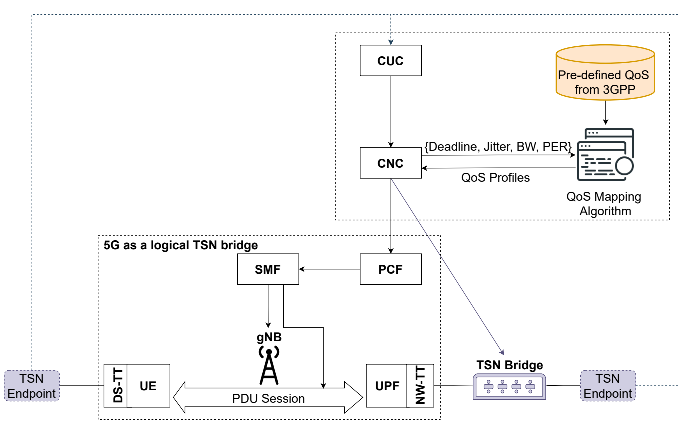

Fig. 2: The centralized configuration model of a TSN-5G network.

A. 5G QoS Characteristics

3GPP Release 16 [5] provides predefined QoS profiles based on the type of service that is used. The QoS profiles are represented by a 5G QoS Identifier (5QI), which is a reference to a set of predefined QoS characteristics. The set of QoS characteristics includes:

- Resource type - The QoS flows can be Guaranteed Bit Rate (GBR), Delay-critical Guaranteed Bit Rate (DC-GBR), or Non-Guaranteed Bit Rate (Non-GBR). In case of GBR flows, 5G pre-allocates dedicated resources in a radio base station.
- Default priority level - Each QoS flow has its own priority level, used to prioritize between different flows of a UPF.
- Packet Delay Budget (PDB) - It defines an upper bound of the time a packet can spend within 5G system without being dropped.
- Packet Error Rate (PER) - Similarly to packet loss rate, in 5G PER defines the number of packets that could not be successfully delivered to the corresponding receiver.
- Default Maximum Data Burst Volume (MDBV) - 5G defines the largest amount of data that can be transmitted by the radio unit within the PDB period.
- Default Average Window - It indicates the duration of time to calculate two QoS parameters of a 5G network: (i) the Guaranteed Flow Bit Rate (GFBR), and (ii) Maximum Flow Bit Rate (MFBR).

This set of predefined 5G QoS characteristics is saved in the knowledge database of pre-defined QoS from 3GPP, presented in Fig. 2.

B. QoS Mapping Algorithm

A QoS mapping algorithm [6] is introduced to map the TSN QoS requirements to the predefined 5G QoS characteristics represented by the 5QI. This algorithm takes two inputs:

1) The predefined QoS characteristics from 3GPP Release 16, which are saved in a knowledge database.
2) The set of TSN QoS-es i.e, Deadline, Jitter, Bandwidth (BW), and Packet Error Rate (PER).

The QoS Mapping algorithm compares the TSN QoS to the predefined 5G QoS-es and chooses the set of characteristics that fulfills the requested QoS based on specific functions presented in [6]. After performing all its calculations the algorithm sends to the CNC the 5G QoS Flow Identifier which will be used for further forward treatment of the flow inside the 5G system.

C. TSN-5G Sample Workflow

This section describes the sample workflow in the proposed TSN-5G architecture which includes TSN bridges and 5G as a logical TSN bridge. The workflow is as follows:

- **Step 1:** The CUC collects all the requirements of various applications in the network from the TSN endpoints and forwards them to the CNC.
- **Step 2:** The CNC has all the knowledge on the capabilities and boundaries of the bridges in the network in advance. It also has the traffic information of the entire network, which it can derive from the communication requirements received from the CUC. Based on network and traffic information, the CNC computes a schedule for the requested TSN flows.

- **Step 3:** In our architecture, if a TSN flow has a receiver connected through the 5G system, the CNC will have to perform another step, which consists of mapping the TSN QoS requirements to the 5G QoS Fig. 2. After obtaining the specific 5G QoS Identifier, the CNC computes the schedule for the 5G system, and shares the 5G QoS Identifiers to the Policy Control Function (PCF) of each 5G system for further traffic forwarding treatment.
- **Step 4:** The CNC configures all the bridges, regardless of whether they are TSN or 5G, following the calculated configuration. To that, we propose to use NETCONF [17], a network configuration protocol that follows a client-server architecture. The CNC has a NETCONF client which triggers the configuration of all the network devices. Each device has a NETCONF server embedded which will read the information received from the CNC and will apply it. In order for the 5G systems to communicate with the CNC, we need to define a YANG data model that specifies which information the PCF will use to configure the QoS-es of the traffic. The definition of the YANG data model is left as future work.

IV. Summary and Ongoing Work

TSN standards and 5G are promising technologies to build the networks of future IIoT systems, as both technologies are suitable for providing flexibility, high-bandwidth and low-latency to the communications. However adequate mechanisms must be put in place to support adequate forwarding of the traffic in TSN-5G networks. One key aspect is the mapping of TSN traffic to 5G QoS profiles to ensure that the timing guarantees of the traffic are met.

Currently, most works propose to use a simple mapping based on TSN's traffic priorities to 5G QoS profiles. However, this mapping cannot take full advantage of the 5G profiles, which can result in the loss of QoS. For this reason, we proposed to use a mapping technique that uses knowledge of the traffic characteristics to carry out a more accurate mapping. To support this mapping technique, we defined an adequate network architecture.

In this work, we proposed to use TSN's fully centralized architecture to carry out the mapping of TSN traffic to 5G. We discussed the main aspects of the architecture, i.e., which devices are involved and how they inter-operate. Furthermore, we proposed a workflow, which defines the different activities required to properly configure a TSN-5G network using the proposed architecture.

Currently, we are working on providing a YANG model that defines the different aspects to be configured in the 5G systems to adequately forward TSN traffic following the results of the proposed mapping. The result of this mapping approach will be the end to end scheduling algorithm for TSN-5G network. We plan to implement the entire approach in a well-known simulator named NeSTiNg, that is based on the OMNeT++ tool.

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