QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows

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***Abstract*—Integrating wired Ethernet networks, such as Time-Sensitive Networks (TSN), to 5G cellular network requires a flow management technique to efficiently map TSN traffic to 5G Quality-of-Service (QoS) flows. The 3GPP Release 16 provides a set of predefined QoS characteristics, such as priority level, packet delay budget, and maximum data burst volume, which can be used for the 5G QoS flows. Within this context, mapping TSN traffic flows to 5G QoS flows in an integrated TSN-5G network is of paramount importance as the mapping can significantly impact on the end-to-end QoS in the integrated network. In this paper, we present a novel and efficient mapping algorithm to map different TSN traffic flows to 5G QoS flows. To the best of our knowledge, this is the first QoS-aware mapping algorithm based on the application constraints used to exchange flows between TSN and 5G network domains. We evaluate the proposed mapping algorithm on synthetic scenarios with random sets of constraints on deadline, jitter, bandwidth, and packet loss rate. The evaluation results show that the proposed mapping algorithm can fulfill over 90% of the applications' constraints.**

I. INTRODUCTION

Many contemporary industrial communication systems are based on wired Ethernet networks. Despite having many advantages, these networks suffer from low flexibility and have high installation and maintenance costs [1]. These shortcomings of wired networks in industrial systems have paved way for wireless communication networks, like WIFI, 4G and 5G, to mention a few. In a wireless communication system, various devices strive to link with each other in a limited capacity of radio spectrum [2]. The advancement in modern wireless and cellular communication technologies have expanded the capacity and coverage of industrial communication systems.

The advantages of both wired and wireless networks can be utilized in industrial communication systems by integrating these networks in a unified heterogeneous wired/wireless network. In such a network, each (sub) network may implement a different protocol and may have different Quality of Service (QoS) characteristics of the underlying flows. In order to achieve a seamless and unified heterogeneous network, the QoS characteristics of the flows need to be systematically mapped in-between different (sub) networks [3], [4]. The estimation of end-to-end QoS of flows in such networks is a critical challenge [6]. One way to measure the overall performance of heterogeneous networks is by quantifying the effects of each participating application and access technology [7].

The fifth generation of mobile networks (5G), as defined by the 3rd generation partnership project (3GPP)[1], support multiple broadband networks providing end-to-end QoS guarantees. The 3GPP Releases define standardized QoS classes/profiles for different services' needs, which makes the mapping of QoS classes over heterogeneous networks a daunting task [3]. Time-Sensitive Networking (TSN) is a set of standards based on switched Ethernet[2] that supports high-bandwidth and low-latency wired communication [9], [10]. On the other hand, 5G offers promising solution to support ultra-reliable low latency communication (URLLC) [11]. The integration of TSN and 5G would provide greater level of flexibility in the network communication, while supporting the high-bandwidth and low-latency communication needs of many industrial communication systems that utilize both wired and wireless networks. Alas, the 3GPP specifications do not define a mapping of QoS attributes between 5G and TSN. Defining such a mapping in a systematic way is a non-trivial task and has a profound impact on the end-to-end QoS experienced by the traffic flows in a heterogeneous TSN-5G network.

In this paper, we propose a novel algorithm, called the QoS-MAN, to systematically map QoS characteristics between TSN and 5G. The purpose of this algorithm is to facilitate integration of traffic flows in a heterogeneous TSN-5G network. Although we specifically considered TSN as the Ethernet protocol in this mapping, the proposed algorithm can be adapted to the flows between 5G and other Ethernet protocols that provide strict QoS.

The main contributions in this paper are as follows:

1) We introduce an efficient QoS mapping algorithm that systematically maps TSN traffic flows or any Ethernet-based traffic flows to different 5G QoS flows, using the QoS characteristics standardized in the 3GPP Release 16 [13]. To the best of our knowledge, this is the first work that systematically maps the flows between Ethernet and 5G network domains using a QoS-aware mapping algorithm.
2) To evaluate the proposed algorithm, we generate synthetic scenarios with random sets of applications' constraints to show how the algorithm performs with respect to fulfilling the applications' constraints.

The rest of the paper is organized as follows. Section II presents the background and related work. The proposed mapping algorithm is presented in Section III, while Section IV provides evaluation and results. Finally, the conclusion and future work are presented in Section V.

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[1] https://www.3gpp.org/

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

II. BACKGROUND AND RELATED WORK

A. 5G network

Each 5G user equipment establishes a Packet Data Unit (PDU) similar to the concept of a Packet Data Network (PDN) connection in 4G, thus we describe the PDU session details and traffic flow management. 5G network provides connectivity to User Equipment (UE) towards a Data Network (DN) such as Internet, IP Multimedia Subsystem (IMS), or any private corporate network. To provide this end-to-end connectivity, 5G establishes a PDU session through the User Plane Function (UPF), containing up to 64 QoS flows. A UE may also request to establish multiple PDU Sessions in parallel [14], e.g, when a UE wants to use both Internet connectivity as well as IMS services at the same time. A 5G QoS flow is assigned to every flow or packet coming to the uplink (UL) or downlink (DL). There are two types of flows in 5G: (i) Guaranteed Bit Rate (GBR) QoS flows and (ii) Non-GBR QoS flows. The GBR transmission is used for applications when providing real-time services, as there are no problems associated with overload during transmission of this data and packet loss [15].

QoS flow is the finest granularity of QoS differentiation inside a PDU session. It has a unique QoS flow Identifier (QFI). The traffic with the same QFI within a PDU session will receive the same traffic forwarding treatment [16]. Considering the DL direction the insertion of QFI is performed on the UPF by the Session Management Function (SMF). The SMF extracts the QoS flow binding parameters (in the following section) and creates a new QoS flow if the one requested does not exist. Each application gets its own Service Data Flow (SDF) inside the UPF, and then they are associated/mapped to different or same QFI based on their QoS needs as also shown in Fig. 1. Another mapping is performed on the radio side, assigning QoS flows to Data Radio Bearers (DRB). However, this type of mapping is beyond the scope of this work.

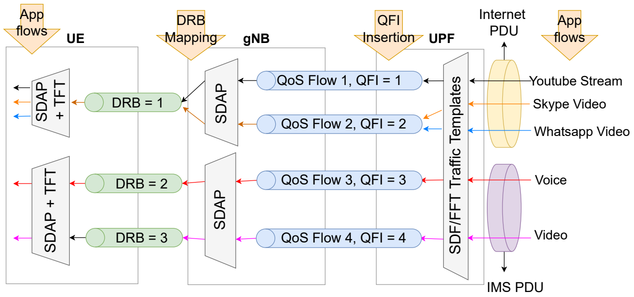


Fig. 1. Example of QoS realization for downlink packets [17].

B. Traffic Forwarding and Traffic Classes in TSN

TSN is a set of standards developed to support high-bandwidth and low-latency communication over switched Ethernet. TSN switches support 8 different priorities defined by Priority Code Point (PCP) field. The PCP is a 3-bit value added in the 802.1Q-2018 VLAN tag. There are two scheduling mechanisms available in TSN: (i) Credit-based shaper for Audio-Video Bridging (AVB), and (ii) Time-Aware Shaper (TAS), which allows arbitration of traffic at the egress port. Each queue is controlled by a Gate Control List (GCL) where all the offline schedule is timestamped.

TSN supports three different traffic classes: Scheduled Traffic (ST), Audio Video Bridging with Class A and Class B, and BE traffic. The ST class is scheduled offline, with strict temporal isolation achieved with the TAS mechanism controlled by the GCL [18]. The GCL is pre-defined with the specific time slots. When a gate has an open state, the corresponding queue is allowed to send messages over the link. This makes ST class fully deterministic, with no jitter on delivering the messages.

AVB defines two priority classes, class A and B, with A as the highest priority queue. The AVB traffic queues are controlled by the CBS mechanism [19]. The CBS works on credit basis, thus the queue consumes credit when it sends a message, and it replenishes the credit when it has a pending message. The traffic from an AVB queue can be transmitted only if the queue has a non-negative credit and if the gate has an open state. The BE traffic class consists of non-critical data with no real-time guarantees. It is the lowest priority class, and traffic from this queue can be sent only if the gate is opened.

C. Related Work

There are several QoS mapping techniques between different network protocols that have been proposed in the literature. These works are categorized based on the mapping between parameters and traffic classes in each network protocol. In this section, we present an overview of the existing mapping techniques between different networks.

Satka et al. [12] developed a translation technique between TSN and 5G frames by mapping the default priority value of a 5G frame to the Priority Code Point (PCP) value of a TSN frame, and vice versa. The QoS-MAN algorithm considers this technique as an input. In comparison, QoS-MAN considers the entire set of predefined 5G QoS parameters, and instead of mapping those parameters to the priority levels of TSN frames, it elaborates further on the applications' requirements such as deadline, jitter, bandwidth, and packet loss. Al-Shaikhli et. al [3] propose a mapping framework for end-to-end QoS support over heterogeneous networks. The mapping framework consists of two scheduling policies: (i) a Class-Based Weighted Fair Queuing (CBWFQ) policy and (ii) a Rate-Controlled Priority Queuing (RCPQ) policy. The authors provide classification of the incoming traffic into appropriate QoS classes based on application's type and QoS requirements (latency, packet loss rate, bandwidth) similar to our work.

The work in [20] presents an effective QoS mapping method between the 5G QoS flow and the time and wavelength-division-multiplexed passive optical network (TWDM-PON) priority queue. TWDM-PON supports queue oriented QoS management introducing high, medium and low priority queues. This work maps the 5G QoS identifiers (22 in total) to the priority queues of PON based on the delay tolerance of services. The network load is also considered as it can affect the mapping relationship, e.g, when the traffic load is small, the backhaul network has more free resources to handle more priority queues. In addition, Zhang et.al [21] present a QoS-aware dynamic scheme to realize the interconnection between 5G and TSN networks. Differently from our work, they focus on the Virtual Network Function (VNF) mapping problems. They propose VNF mapping considering mixed integer linear programming with time-sensitive constraints together with a heuristic algorithm for VNF mapping and scheduling in the 5G-TSN network. Yang et al. [22] propose a scheme for low-latency transmission and resource management in a TSN-5G system. They include a QoS mapping table of TSN QoS information and 5G QoS Identifier (5QI) mapping table. This work focuses on uplink transmission schemes based on configured grant scheduling instead of mapping QoS containers in order to satisfy delay requirements of the applications.

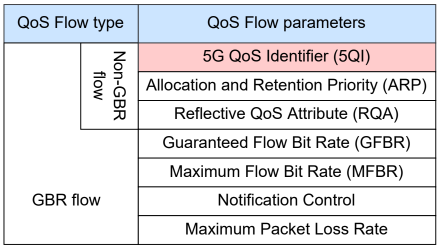
Reviewing the existing works on QoS mapping algorithms, we observe that none of them support mapping TSN traffic into 5G. In this paper, we present such an algorithm and we show that the proposed algorithm, supports traffic mapping of Ethernet in general, but specifically TSN traffic to 5G traffic.

III. PROPOSED QOS MAPPING FOR TSN-5G FLOWS

Traversing traffic from TSN to 5G requires a mapping from TSN QoS to 5G QoS. This mapping provides an appropriate forwarding treatment to TSN traffic inside the 5G system. In this section, first we define the QoS parameters and characteristics in 5G. Then we present the proposed mapping algorithm that can map not only TSN but also other Ethernet traffic to 5G flows based on the application's requirements.

A. 5G QoS Parameters and characteristics

The 5G QFI is a reference to a set of QoS parameters depending on the type of 5G QoS flow. This set of QoS Parameters is presented in Fig. 2. The focus of this paper is on 5G QoS Identifier (5QI). The detailed information for other QoS parameters from Fig. 2 can be found in [13].



QoS Flow type		QoS Flow parameters
GBR flow	Non-GBR flow	5G QoS Identifier (5QI)
		Allocation and Retention Priority (ARP)
		Reflective QoS Attribute (RQA)
		Guaranteed Flow Bit Rate (GFBR)
		Maximum Flow Bit Rate (MFBR)
		Notification Control
		Maximum Packet Loss Rate

Fig. 2. 5G QoS flow types and their parameters.

5QI is a scalar referencing to a set of predefined QoS characteristics, as shown in Fig. 3. The 3GPP Release 16 [13] provides predefined values for each characteristic based on the type of service that is used. The set of characteristics includes:

- *Resource Type:* it determines whether dedicated resources are pre-allocated to a QoS flow in a radio base station. The flows can be Guaranteed Bit Rate (GBR), Delay-critical Guaranteed Bit Rate (DC-GBR), or Non-Guaranteed Bit Rate (Non-GBR). There are no pre-allocated resources for Non-GBR flows. On the other hand, GBR and DC-GBR flows are typically authorized "on demand", with the only difference that for DC-GBR, 3GPP specifies an extra characteristic, namely the Maximum Data Burst Volume, which will be described below.

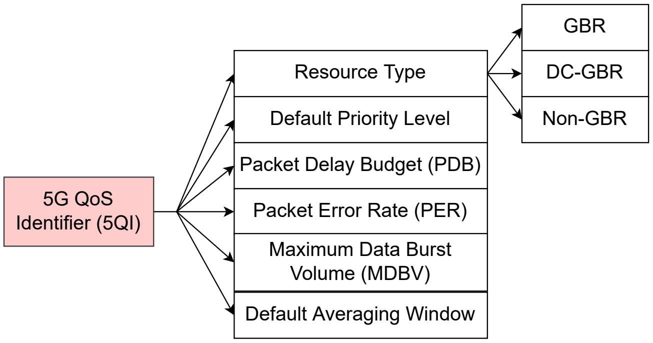


Fig. 3. Standardized 5G QoS Characteristics.

- *Default Priority Level:* it indicates priority level of QoS flows. The smaller the number the higher the priority level.
- *Packet Delay Budget (PDB):* it defines an upper bound on the time a packet is delayed between UE and UPF. It is basically the time a packet can spend inside 5G system without being dropped.
- *Packet Error Rate (PER):* it defines an upper bound on the rate of packet losses, which is formally defined as the number of packets that have been sent by a link layer protocol, yet they could not be successfully delivered to the corresponding receiver.
- *Default Maximum Data Burst Volume:* it defines the largest amount of data that the 5G Radio Access Network is required to transmit within the PDB period.
- *Default Averaging Window:* it indicates the duration of time to calculate the GFBR and MFBR.

B. QoS-MAN algorithm

We propose a QoS Mapping Algorithm, called the QoS-MAN, to efficiently map Ethernet traffic flows to 5G QoS flows. The QoS-MAN algorithm uses application constraints and requirements, which can be defined for TSN or other Ethernet-based network flows. For the sake of simplicity, we divide our algorithm into two phases. In the first phase, the algorithm maps the Ethernet traffic flows to 5G resource types. Whereas in the second phase, the algorithm maps the traffic flows to specific 5G QoS Identifiers. The two phases are described in detail below.

1) ***Phase 1 – Mapping to 5G resource types:*** 5G provides three types of resources, namely DC-GBR, GBR, and Non-GBR. Mapping TSN traffic flows to 5G QoS flows consists of mapping TSN traffic classes to 5G resource type that best fits to the TSN traffic needs. First, we present a naive mapping technique to map the TSN traffic classes to 5G resource types. As the ST traffic in TSN is fully deterministic with zero jitter on delivery of packets, it should be mapped to DC-GBR flows on a 5G system. The DC-GBR flows in 5G are authorized on demand using permanently pre-allocated resources, thus providing real-time guarantees on a PDB period with a MDBV.

AVB traffic in TSN is relatively less critical than ST traffic. Therefore, this traffic may or may not have hard real-time requirements. However, it still needs pre-allocation of radio resources to prevent suffering from lack of resources at any point in time. The GBR flows provide such guarantees. Therefore, AVB traffic is mapped to the GBR resource type.

The BE traffic in TSN is commonly referred to as non-critical traffic with no real-time requirements. Hence, this traffic is mapped to the Non-GBR flows in the 5G network. The naive mapping technique can be presented as follows.

$$\textit{DC-GBR} \longleftarrow \textit{ST}$$
$$\textit{GBR} \longleftarrow \textit{AVB}$$
$$\textit{Non-GBR} \longleftarrow \textit{BE}$$

However, the naive technique of mapping TSN and 5G flows, discussed above, neither ensures any specific QoS for the packets nor fulfillment of the application's constraints. Instead, the technique only maps the packets based on their traffic class, e.g, AVB class can consist of critical data with real-time requirements that needs to be distinguished from other AVB traffic with no criticality or real-time requirements. The naive mapping technique maps all such AVB traffic in a similar fashion to the 5G flows regardless of the real-time requirements. Another limitation of the naive mapping technique is that it does not consider the bandwidth or packet loss rate constraints of an application while performing the mapping between TSN and 5G flows.

In order to deal with the above mentioned limitations of the naive mapping technique, we present an extended technique by developing three logic-based equations for each type of resource. The technique uses the application requirements as its input. We define these requirements in the form of constraints such as the Deadline constraint (DL), Jitter constraint on delivery of packets (JO), and Bandwidth constraint (BW). All parameters are treated as Boolean variables. A non-zero parameter means that the application has a requirement on that specific parameter, otherwise the application does not impose any requirement on the parameter. The algorithm first checks if the application has real-time requirements or not. In this work, these requirements correspond to the deadline or jitter constraints on the packets send by the application.

An application is assigned a Non-Guaranteed Bit Rate (Non-GBR) resource if it does not have any real-time requirement on the reception of flows.

$$\textit{Non-GBR} = !\ (\textit{DL} \,\|\, \textit{JO})$$

If an application has real-time requirements (deadline, jitter or both) but does not have bandwidth constraints, then the Guaranteed Bit Rate (GBR) flow type is assigned to it. However, if an application has real-time requirements as well as constraints on the throughput or bandwidth, then it is assigned the Delay-Critical Guaranteed Bit Rate (DC-GBR) resource type.

$$\textit{GBR} = (\textit{DL} \,\|\, \textit{JO})\ \&\ !(\textit{BW})$$
$$\textit{DC-GBR} = (\textit{DL} \,\|\, \textit{JO})\ \&\ \textit{BW}$$

We summarize the mapping equations with a truth table shown in Table I, where 1 identifies availability of the constraint, while 0 identifies otherwise. Note that X shows that the constraint can have any binary value.

The pseudocode of QoS-MAN algorithm is presented in Algorithm 1. This algorithm takes the number of applications and applications' constraints (i.e., Deadline, Jitter, Bandwidth, and Packet Error Rate) as inputs, and maps them to different 5G resource types using the logical equations presented above. The functions $MappingToDC(i)$, $MappingToGBR(i)$, and $MappingToNonGBR(i)$ will be described in Phase 2.

TABLE I

TRUTH TABLE OF THE MAPPING TECHNIQUE.

DL	JO	BW	GBR	DC-GBR	Non-GBR
0	0	X	0	0	1
0	1	0	1	0	0
0	1	1	0	1	0
1	0	0	1	0	0
1	0	1	0	1	0
1	1	0	1	0	0
1	1	1	0	1	0

Algorithm 1 QoS-MAN algorithm.

```
begin
$n \leftarrow number\_of\_apps$
$applicationRequiements \leftarrow user\_input$
$NonGBR\_matrix \leftarrow predefined\_NonGBRqos$
$GBR\_matrix \leftarrow predefined\_GBRqos$
$DC\_GBR\_matrix \leftarrow predefined\_DC\_GBRqos$
for $application[i]$ where $i \leftarrow 1$ to $n$ do
    if $app[i].Deadline || app[i].Jitter$ then
        if $app[i].Bandwidth$ then
            $QoS[i].resourceType \leftarrow DelayCriticalGBR$
            $MappingToDC(i)$
            return $QosProfile[i]$
        else
            $QoS[i].resourceType \leftarrow GBR$
            $MappingToGBR(i)$
            return $QosProfile[i]$
        end if
    else
        $QoS[i].resourceType \leftarrow Non\_GBR$
        $MappingToNonGBR(i)$
        return $QosProfile[i]$
    end if
end for
end
```

2) ***Phase 2 – Mapping to 5G QoS identifiers:*** For each type of resource, the 3GPP Release 16 [13] defines a set of values for QoS characteristics, i.e., PDB, PER, MDBV, as described in Section II. A 5G QoS Identifier is used as a reference to the predefined values of QoS characteristics. In our approach, 5QI is equivalent to QoS Flow Identifier (QFI), used as a unique value to identify the QoS flow. There are 5 possible QFI-s for DC-GBR, 12 QFIs for GBR, and 9 QFI-s for Non-GBR as shown in Tables II, III, and IV used as an input to the QoS-MAN algorithm. Phase 2 of the algorithm efficiently assigns QFIs to specific traffic flows based on the values of deadline, bandwidth and packer error rate, if any.

The 3GPP Release 16 defines the information for DC-GBR resources presented in Table II, where the Guaranteed Bandwidth is calculated by dividing the Maximum Data Burst Volume (MDBV) with the Packet Delay Budget (PDB):

$$BW = \frac{MDBV}{PDB}$$

Algorithm 2 uses the predefined values from Table II to map traffic flows to specific QFIs based on the application's bandwidth constraint.

TABLE II
QFIs for standardized Delay-Critical GBR flows.

QoS/ QFI	Priority	Guaranteed Bandwidth (Mbit/s)	Packet Error Rate (PER)
86	18	2.1664	10^{-4}
82	19	0.204	10^{-4}
85	21	0.408	10^{-5}
83	22	1.0832	10^{-4}
84	24	0.361	10^{-4}

Algorithm 2 *MappingToDC(i)*

```
begin
1:  $i \leftarrow applicationID$
2:  $QoSBW \leftarrow findClosestBW(DC\_BW, 5, app[i].BW)$
3:  for $k \leftarrow 0$ to 4 do
4:      if $DC\_GBR[k][1] == QoSBW$ then
5:          $QoS[i].identifier \leftarrow DC\_GBR[k][0]$
6:          $break;$
7:      else
8:          $QoS[i].identifier \leftarrow 500$
9:      end if
10: end for
end
```

Algorithm 2 takes the application's bandwidth and compares it to guaranteed bandwidth values from Table II, defining the closest higher guaranteed bandwidth depicted as QoSBW - line 2 of Algorithm 2. Then, the traffic flow is assigned to the identifier that assures the specific QoSBW that best fulfills the application's requested bandwidth, and exits the loop. If there is no QFI which assures the requested bandwidth then we assign the application to a non-significant QFI (500) saying that the algorithm failed to fulfill the application's BW using the standardized DC-GBR flows.

To map traffic flows to QoS flows of GBR resource type, we use the values of the standardized QoS characteristics' from 3GPP shown in Table III.

TABLE III
QFIs for standardized GBR flows.

QoS/ QFI	Priority	Packet Delay Budget (PDB)(ms)	Packet Error Rate (PER)
3	30	50	10^{-3}
65	7	75	10^{-2}
67	15	100	10^{-3}
1	20	100	10^{-2}
66	20	100	10^{-2}
2	40	150	10^{-3}
71	56	150	10^{-6}
4	50	300	10^{-6}
72	56	300	10^{-4}
73	56	300	10^{-8}
74	56	500	10^{-8}
76	56	500	10^{-4}

The QoS-MAN algorithm takes these values as an input to effectively choose the right QFI value for the traffic flow of each application as shown in Algorithm 3. First, the algorithm searches column 3 in Table III to find the PDB value that is closest to (but lower than) the deadline constraint of each application depicted as QoSPDB - line 2 of Algorithm 3. From Table III one can notice that there are many identifiers that have the same PDB value but have different PERs. To better assign the QFI, in line 5 of Algorithm 3 we make sure that the algorithm selects the QFI that assures a PER greater than or equal to the application's PER constraint, and exits the loop. If the application's constraints (PER, PDB) cannot be assured from the GBR Qos then we assign a non-significant (400) identifier saying that the algorithm failed to assign this application to a GBR QoS flow.

Algorithm 3 *MappingToGBR(i)*

```
begin
1:  $i \leftarrow applicationID$
2:  $QoSPDB \leftarrow findClosest(GBR\_PDB, 12, app[i].DL)$
3:  for $k \leftarrow 0$ to 11 do
4:      if $GBR[k + temp][2] == QoSPDB$ then
5:          if $GBR[k + temp][3] \geq app[i].PER$ then
6:              $QoS[i].identifier \leftarrow GBR[k + temp][0]$
7:              $break;$
8:          end if
9:      else
10:         $QoS[i].identifier \leftarrow 400$
11:     end if
12: end for
end
```

Lastly, for QoS flows of Non-GBR resource type we use the standardized values from Table IV. The pseudocode presented in Algorithm 4 uses the PER to map to Non-GBR QFIs, using column 3 in Table IV. Non-GBR QFIs can assure only flows with PER less than or equal to $10^{(-6)}$.

TABLE IV
QFIs for standardized Non-GBR flows.

QoS/ QFI	Priority	Packet Error Rate (PER)
69	5	10^{-6}
5	10	10^{-6}
70	55	10^{-6}
6	60	10^{-6}
79	65	10^{-2}
80	68	10^{-6}
7	70	10^{-3}
8	80	10^{-6}
9	90	10^{-6}

As the majority of QFIs assure a PER up to the power of (-6), our algorithm uniformly assigns traffic flows to different QFIs without overusing only one flow. To do so, the QoS-MAN algorithm reserves QFI 79 and QFI 7 to flows with PERs 10^{0} and 10^{-1} respectively, as shown on lines 2-6 of Algorithm 4, otherwise the algorithm selects between other QFIs. We use the temp variable to make sure the algorithm does not select the same QFI for every flow.

If there is no QFI that assures the requested PER, then the application is assigned to a non-significant QFI saying that the algorithm failed to fulfill the application's PER using the Non-GBR flows.

IV. EVALUATION AND RESULTS

In this section, we present our experimental setup showing the performance of QoS-MAN on a set of evaluation scenarios.

A. Experimental setup

We consider 1000 applications with different QoS constraints on Deadline, Jitter, Bandwidth and Packet Error Rate. It is common for real-time systems to have tasks operating in different time bands [23]. The usual time bands for real-time

Algorithm 4 *MappingToNonGBR(i)*

```
begin
  $i \leftarrow applicationID$
  if $app[i].PER == 0$ then
      $QoS[i].identifier \leftarrow Non\_GBR[4][0]$
  end if
  if $app[i].PER == 1$ then
      $QoS[i].identifier \leftarrow Non\_GBR[6][0]$
  end if
  if $app[i].PER > 1$ then
      for $k \leftarrow 0$ to $8$ do
          if $app[i].PER \leq Non\_GBR[k + temp][2]$ then
              $QoS[i].identifier \leftarrow Non\_GBR[k + temp][0]$
              $temp + +;$
              if $Non\_GBR[k + temp][2] == 2 || Non\_GBR[k + temp][2] == 3$ then
                  $temp + +;$
              end if
              if $temp > 8$ then
                  $temp = 0;$
              end if
              $break;$
          end if
      end for
  else
      $QoS[i].identifier = 0$
  end if
end
```

systems are 1 ms-10 ms, 10 ms-100 ms, 100 ms-1 s [24]. For example, a temperature sensor will likely sample at a lower rate compared to a rotation speed sensor [25]. Considering the examples above, in our scenarios we consider real-time systems with tasks operating in a time band of 100 ms-1 s. We also randomly select the deadlines within the range of [100 ms-1 s]. The random selection of deadlines follows uniform distribution.

Jitter constraints are defined by random boolean values as we use them only in the first phase of the mapping algorithm, following the logic-based equations in Section III. In addition, the bandwidth constraints are set to uniformly-distributed values in the range of [0%-100%]. 100% is the maximum guaranteed bandwidth of ≈ 2.16 Mbit/s as shown in Table II. Zero is used as a boolean value to specify no bandwidth constraint.

We use packet error rates (PERs) to evaluate the performance of our algorithm. To get different ranges for PERs, we consider values from previous works (i) Packet Error Rates for in-body communication [26], and (ii) Packet Error Rates for a Mobile Wireless Access System [27] as shown in Table V. We also evaluate QoS-MAN algorithm for PER values in the range of predefined possible PER from 3GPP specifications.

TABLE V
PER VARIATIONS USED TO EVALUATE THE QOS-MAN ALGORITHM.

Evaluation Scenarios	PER (ranges)
PERs for in-body communication [26]	$[10^{-12} - 10^{0}]$
PERs for a Mobile Wireless System [27]	$[10^{-5} - 10^{0}]$
Possible PERs for predefined QFIs in 5G [13]	$[10^{-8} - 10^{0}]$

B. Analysis of mapping results for different ranges of PER

We use three different scenarios to evaluate the performance of the QoS-MAN algorithm. The input to the algorithm is selected from different ranges of PER. In the first scenario, the application's constraints on PER are set to uniformly-distributed values in the range of $[10^{-12} - 10^{0}]$. Whereas, in the second and third scenarios, the PER values are set in the range of $[10^{-5} - 10^{0}]$ and $[10^{-8} - 10^{0}]$, respectively, as shown in Table V. The main idea in this evaluation is to show the sensitivity of the proposed algorithm with respect to different PER inputs.

The results of QoS-MAN for scenario 1 are presented in Fig. 4. It is obvious that 5G QoS resource types of GBR and Non-GBR failed to fulfill some of the applications' constraints when the PER is set in the range of $[10^{-12} - 10^{0}]$. This result was expected since predefined 5G QoS flows support PERs down to the level of 10^{-8}. Any PER value less than 10^{-8} cannot be guaranteed by the predefined QFIs of the 5G system. The DC-GBR flows are not affected by PER constraints since the QoS-MAN algorithm selects the DC-GBR QFIs only on the basis of the Bandwidth constraint of the application.

We conclude that in scenario 1 the QoS-MAN algorithm can fulfill only 79.3% (shown in Fig. 7) of the applications' constraints since we are mapping the traffic flows to the predefined QFIs supporting PERs down to the level of 10^{-8}.

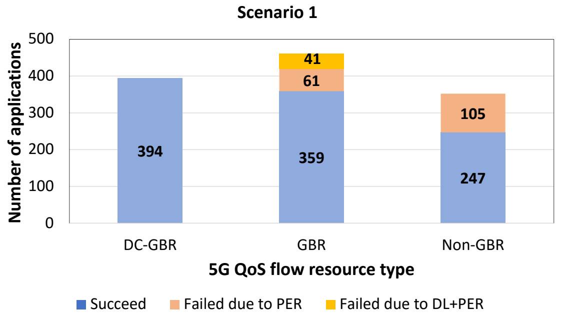


Fig. 4. Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-12} - 10^{0}]$.

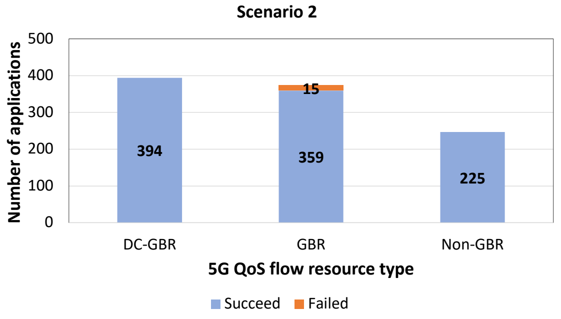


Fig. 5. Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-5} - 10^{0}]$.

The results of QoS-MAN for scenario 2 are presented in Fig. 5. We run the algorithm with the same number of applications, but changing PER in ranges of $[10^{-5} - 10^{0}]$. The performance of the algorithm is significantly improved fulfilling 98.5% (shown in Fig. 7) of the applications' constraints as predefined QFIs of all resource types can guarantee PERs in the ranges of $[10^{-5} - 10^{0}]$. When it comes to GBR type of resources, our algorithm checks both DL and PER of the applications, and it might fail to assign it to a QFI which can fulfill the DL constraint but not the PER constraint and vice versa. For example in the case of a traffic flow with a deadline value of 100ms and a PER of 10^{-6}, there is a set of predefined QFI(33, 65, 67, 1, 66) in Table III that can guarantee the deadline value of 100 ms but not the PER value of 10^{-6}.

If we consider PERs in the ranges of predefined QoS characteristics in 5G, the QoS-MAN algorithm fulfills 89.7% (shown in Fig. 7) of the applications' constraints, failing 63 applications' constraints in PER from Non-GBR QoS flows (which can only guarantee PER down to the level of 10^{-6} in Table IV), and 40 applications' constraints in DL and PER from GBR QoS flows as shown in Fig. 6.

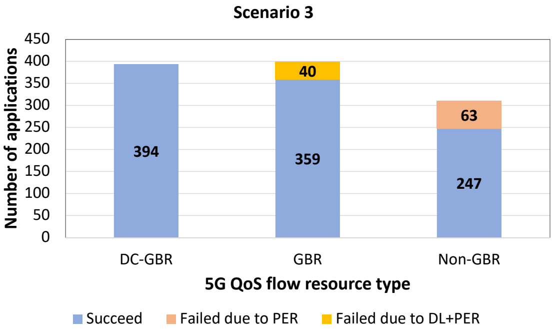


Fig. 6. Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-8} - 10^{0}]$.

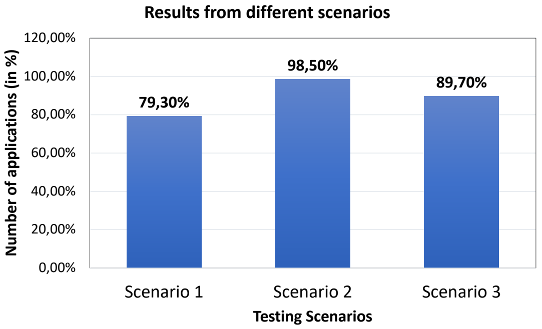


Fig. 7. The percentage of applications whose constraints are fulfilled by QoS-MAN in each scenario.

C. Analysis of traffic flows assigned to each QFI

To further evaluate the performance of the QoS-MAN algorithm, we investigate how the traffic flows are spread among the QFIs. In 5G, all traffic flows with the same QFI are entered to the same QoS flow. In this case, if all traffic flows are assigned to the same QFI then an overhead would be added to the transmission of these flows.

In Figs. 8, 9, and 10, we show how the traffic flows from different applications are mapped to predefined QFIs in a 5G system. There are only 5 possible QFIs for DC-GBR resources, which offer guarantees on very different bandwidth values. In this case, our algorithm is restricted as it depends on the Bandwidth constraint of the application, which in our case is uniformly distributed between values from 1%-90%. QFI 18 serves the majority of traffic flows as it is the only QFI that can guarantee bandwidth constraints over 50% of the maximum 2.16664 Mbit/s, while the remaining 4 QFIs serve the traffic flows with bandwidth constraints less then 50%.

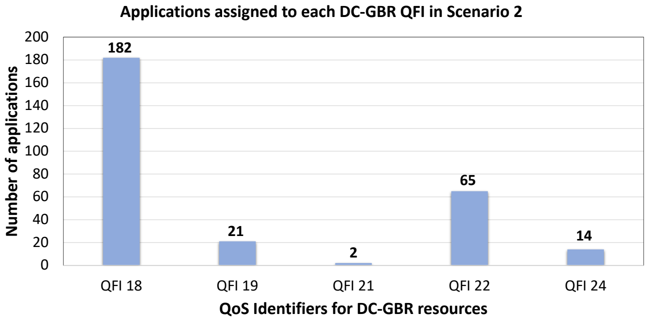


Fig. 8. Number of applications assigned to each DC-GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

Similarly, there are 12 possible QFIs for GBR resources. In this case, the QoS-MAN algorithm performs the mapping by selecting the QFI which fulfills the Deadline and PER constraints of the application. The traffic flows are spread among the QFIs, by first choosing the closest lower value to their deadline constraint and PER constraint. As shown in Fig. 9, QFI 74 is mostly used for the traffic flows. This QFI offers the highest PDB value of 500ms and lowest PER of 10^{-8}. From the user deadline constraints, we claim that the QFI with a PDB of 500ms will serve all the traffic flows with a deadline constraint in the range of [500 ms-1000 ms]. Since the QFI 74 offers the lowest PER of 10^{-8}, it ends up being mostly used by the mapping algorithm. A traffic flow which does not have a deadline constraint but has a jitter constraint is added to QFI 3 and 65 of GBR, selecting the one that provides guarantees in the requested PER.

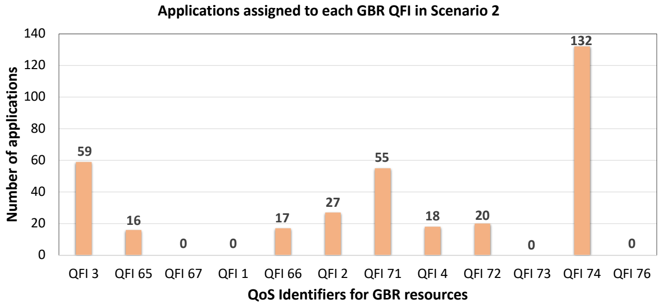


Fig. 9. Number of applications assigned to each GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

The effect of spreading the traffic flows among different QFIs can be clearly observed in Non-GBR resources as most of the QFIs of Non-GBR type guarantee the same PER of 10^{-6}, while QFI 79 and QFI 7 guarantee PER of 10^{-2} and 10^{-3}, respectively. Fig. 10 shows the proposed algorithm does not overuse one QFI, but it indeed spreads the flows between different QFIs to reduce the overhead inside the 5G QoS flows.

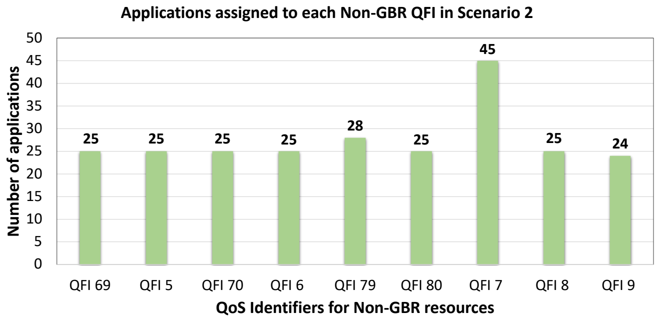


Fig. 10. Number of applications assigned to each Non-GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we advocated that one of the essential but challenging tasks in integrating Time Sensitive Networking (TSN) and 5G networks into a unified heterogeneous network is to map their QoS requirements. Therefore, we proposed a novel mapping algorithm to efficiently map TSN QoS requirements into 5G QoS characteristics. The proposed algorithm, called the QoS-MAN, can systematically and efficiently map any Ethernet traffic flows to 5G QoS flows. We evaluated the proposed algorithm using several synthetic scenarios with random sets of constraints on applications, including deadline, jitter, bandwidth and packet loss rate. The evaluation results show that the proposed mapping algorithm can effectively fulfill over 90% of the applications' constraints.

The proposed algorithm considers only the predefined QoS flow identifiers provided by the 3GPP specification, while there is also the opportunity to create new QoS flows with other identifiers. This can improve the performance of our mapping algorithm by achieving a fulfillment of 100% applications' constraints. Moreover, 5G defines a limitation of maximum 64 QoS flows in a PDU Session, which our mapping algorithm does not take in consideration. The future work entails to address this limitation of QoS flows in the QoS-MAN algorithm, while proposing a scheduling technique for TSN-5G network.

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