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Ethernet for Automotive
Gap Analysis on TSN

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Ethernet for Automotive

Gap Analysis on TSN

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January 15 2016

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List of Abbreviations

ADAS Advanced Driver Assistant Systems

AVB Audio Video Bridging

AVTP Audio Video Transport Protocol

BE Best-Effort

CAN Controller Area Network

CBS Credit-Based Shaper

CDT Control Data Traffic

ECU Electronic Control Unit

FIFO First-In First Out

GCL Gate Control List

GUI Graphical User Interface

HD High-Definition

IEEE Institute of Electrical and Electronics Engineers

IVN In-Vehicle Network

LIDAR LIgth Detection And Ranging

LIN Local Interconnected Network

MAC Media Access Control

MOST Media Oriented Systems Transport

NW-PSP No-Wait Packet Scheduling Problem

OSI Open System Interconnection

PHY Physical Layer

RADAR Radio Detection and Ranging

TAS Time-Aware Shaper

TCP Transmission Control Protocol

TSN Time Sensitive Networking

TTE Time-Triggered Ethernet

V2N Vehicle-to-Network

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Everything

Chapter 1

Introduction

Over the past years, smart mobility has been an increasing trend within Automotive. Many of these can be found from examples as autonomous vehicles, Vehicle-to-Network (V2N), Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) connectivity, possibly equipped with car-sharing capabilities.
With the addition of passive safety systems and enhanced multimedia, to sense, control and display the state per vehicle, the number of vehicle functions has expanded tremendously.
Considering the progress towards fully autonomous driving the Automotive sector is in need of a communication bus with high bandwidth, able of forwarding all this data with real-time guarantees.

Research on the prerequisites for this thesis have focused on the current communication busses in Automotive as well as the introduction of Automotive Ethernet and its currently available standards, Audio Video Bridging (AVB) and Time Sensitive Networking (TSN).
As the present communication busses are not able to provide the bandwidth required for near future vehicle functions, the scope of the thesis has been limited to the examination of Automotive Ethernet.
The sub-standards of both TSN and AVB have been dealt with by many, proposing or justifying the capability of the methods presented within Institute of Electrical and Electronics Engineers (IEEE) 802.1. As the current research is intended to cope with Time Critical data, not being multimedia streams, the scope is again further limited to Automotive Ethernet TSN.

1.1 Problem statement

Modern Automotive, with its trend towards autonomous driving, requires communication busses with high bandwidth and real-time guarantees. This is required to transmit data captured by various cameras and sensors mapping the environment.

Currently available communication busses, such as FlexRay, enable forwarding at a higher and more reliable rate compared to Controller Area Network (CAN), but operate at only moderate speeds of 10 [Mbps]. For this reason, newly introduced communication busses to the Automotive industry should by examined.

A yet often mentioned solution can be found in Automotive Ethernet. This communication protocol is a tailored version of the residential/industrial variant, extended with techniques to assure real-time and redundant communication.

This thesis therefore will focus on the applicability of Automotive Ethernet as a replacement for the current available communication busses. Especially scheduling of a task set and forwarding of data with strict latency guarantees, promised by the TSN standard, is to be analyzed.

Based on the problem statement, the following research questions are formulated and will be answered within this thesis.

1. How can the TSN standard be used on Automotive Ethernet to achieve communication for safety-critical vehicle functions?

   To answer the main research question, two sub-questions are formulated:

   - What is the current application state of Automotive Ethernet related to safety-critical vehicle functions?
   - What are the deficiencies of the TSN standard present while achieving safety-critical vehicle functions?

1.2 Methodology

The methodological approach taken in this study is a mixed methodology based on a gap analysis. First, currently used Automotive communication busses have been studied, supported by the introduction of Automotive Ethernet. The latter is examined through the sub-standards of TSN and present related work to become aware of the intended capabilities and the current level to build up on.
Next, the future state has been defined, in which the importance of the points summarized in the current state is being emphasized. In the end, gaps between the states will be identified which form the base of this thesis.

This study therefore set out to assess the gaps between the current and future state of TSN, attempting to contribute to the development of the standard.

1.3 Outline

The thesis is organized as follows.

Chapter 2 describes the background, comprising the introduction of Automotive Ethernet and its available sub-standards. Moreover, it introduces the TSN standard and the shaper of concern in this thesis.

Chapter 3 provides information about the Gap Analysis being performed. In this chapter, the current Automotive communication busses are being assessed. Next, the future bandwidth requirements are stated. Followed by a gap description presenting the differences between the current and future state, which is the subject of this thesis.

Chapter 4 describes the Time-Aware Shaper standard in more depth, introducing different approaches for implementation of the Guard Band. All to facilitate as much bandwidth to forward unscheduled traffic.

Chapter 5 presents the development of the simulation model. In this chapter the Time-Aware Shaper standard is modeled to be implemented in a TSN switch forwarding data of two transmitting nodes. Besides the development of the model, the procedure and expectations of the simulation will be demonstrated.

Chapter 6 describes the results of the simulation. The schedulability and influence of different Guard Band approaches will be presented, from which the advantage of Automotive Ethernet becomes evident.

Chapter 7 concludes this thesis and answers the research questions stated above.

Chapter 2

Background

2.1 Automotive Ethernet

The increase in electronic devices and electrification of the Automotive sector combined with the increasing trend of autonomous driving and connected vehicles requires more bandwidth than the current communication buses can provide.
For this reason, the OPEN Alliance SIG has been formed, which is a working group encouraging the adoption of Ethernet-based connectivity in Automotive. Unlike the Ethernet used in Industrial/Residential environments this working group collaborates to develop a tailored solution for Automotive. As the abbreviation of the working group describes, OPEN stands for One-Pair Ether-Net, compared to the four- or even eight-wire Ethernet currently known [17].

Automotive Ethernet Standard

The Broadcom company was the first to announce having invented an Automotive Ethernet standard meeting the stringent Automotive requirements, BroadR-Reach [14]. While using a single un-shielded twisted pair the bi-directional communication gains connectivity at 100 [Mbps], at the same time reducing connectivity costs with 80 [%] and the overall vehicle weight with 30 [%].

According to Broadcom, the implementation of BroadR-Reach is ideal to be used in vehicle connectivity and networking applications such as Advanced Driver Assistant Systems (ADAS), gateway Electronic Control Unit (ECU)s, and Infotainment and Instrument cluster applications.
Moving from shared-medium communication buses to point-to-point and switched networks provides flexibility and opportunities for new In-Vehicle Networks [17].

The early adoption of Broadcoms BroadR-Reach in 2011 has later been standardized in IEEE 100-T1, 1000BASE-T1 and 1000BASE-RH.

Automotive Ethernet Protocols

AVB

In 2005 a working group, AVB, has been established within IEEE 802.1 to introduce high-bandwidth network solutions over Ethernet. As the name implies, AVB is used for main application in Audio and/or Video communication.
As a result various specifications were introduced which mutually form the foundation of the AVB stack [12]:

- IEEE 802.1BA; *Audio Video Bridging (AVB) Systems*
- IEEE 802.1AS; *Generalized Precision Timing Protocol (gPTP)*

- IEEE 802.1Qat; *Stream Reservation Protocol (SRP)*
- IEEE 802.1Qav; *Forwarding and Queuing for Time-Sensitive Streams (FQTS)*

The main objectives, achieved by implementing the sub-standards of the AVB protocol, are to [18]:

1. Decrease network delays
2. Time-synchronization of the network
3. Avoid interference from non time sensitive traffic.

Applications

Implementation of the AVB standard synchronizes multimedia streams in home entertainment systems, studios and stadiums. Also the standard is applied in Aeronautic networks for cabin video monitoring systems, crew telephones and passenger addressing [3].
Within the Automotive domain it is especially intended to be used for infotainment and in-vehicle networking. Examples of such AVB implementations are lip-synced multimedia playback, in which a central media player sends out a video stream to, for example, two rear-seat displays and an audio stream on a separate path to an amplifier.

AVB Evolved

The encouraging development and application scope of the AVB standard has led to an increase in possibilities for implementation, eventually with extensions, to be applied in for example safety-related vehicle functions.
For this reason the working group has been renamed to Time-Sensitive Networking, aiming more on message preemption, scheduling and time synchronization for non-AVB traffic [11].

TSN

Operating ADAS requires multiple systems to work in synchronization, forwarding large amounts of data over the network. In case of having to perform an emergency brake operation, the safety systems will directly influence the braking distance. The communication established is, therefore, critical and must be able to perform with confined delays.

For the reason of safety-critical communication bus features. the TSN working group has been initiated, assuring forwarding of a substantial amount of data within a restricted time duration. Along with the already available specifications introduced in AVB, various other specifications have been created, enabling timing guarantees for safety-critical traffic [19]:

- IEEE 802.1Qbv; *Enhancements for Scheduled Traffic*
- IEEE 802.1Qbu; *Frame Preemption*
- IEEE 802.1Qch; *Cyclic Queueing and Forwarding*
- IEEE 802.1AS-REV; *Enhanced Generic Precise Timing Protocol*

The objectives of TSN are:

1. Calculable, guaranteed end-to-end latency

2. Highly limited latency fluctuations
3. Extremely low packet loss

Applications

The specifications of TSN might enable the ADAS to forward data from the Radio Detection and Ranging (RADAR)/LIgth Detection And Ranging (LIDAR) in a misty environment to the control unit in which processing and actuation may take place based upon the sensed variables in the vehicles surroundings.
At the moment of writing, no applications of TSN could be found in production vehicles, all information available was found to be purely theoretical.

Automotive Ethernet Frame

The data frames being forwarded over Automotive Ethernet, for the AVB and TSN standard, have been modified compared to the standard IEEE 802.3 Ethernet frames used in residential/industrial applications, as can be seen from Figure 2.1 in green.
Automotive Ethernet frames consist instead of a Destination Media Access Control (MAC) address a unique multicast address serving as an identifier for a singular network stream. The MAC addresses being generated are moreover distributed to every network switch ensuring the data frames to be forwarded along the correct path. Forwarding frames, once received within a switch, to multiple listeners becomes also a possibility.

In addition to the standard Ethernet frame, a 22-byte header has been added enabling identification and timely tracking of each individual data frame. Identification of each data frame is done through an increasing field labeled *Sequence Number*, making it possible to filter out duplicates and recognize lost frames.
Furthermore, each frame receives a so called *Transmission Time-stamp* assuring that forwarding of the respective frame occurred within the correct time window provided by the scheduler. Transmission times can moreover be calculated subtracting the arrival time within the listener from the time of forwarding within the talker, monitoring the end-to-end delay [9].

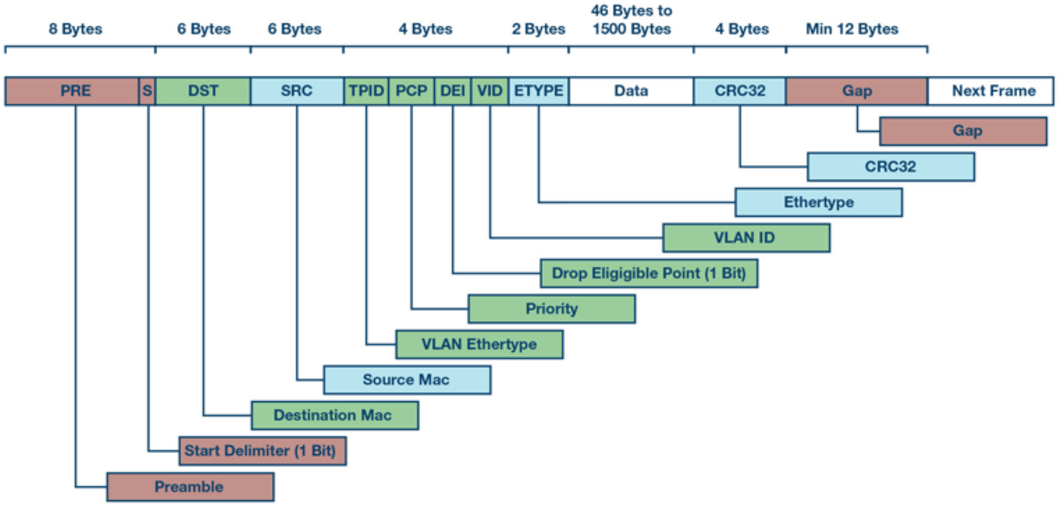

Figure 2.1: Automotive Ethernet Frame

2.2 Time Sensitive Networking

Many applications in Automotive require data frames to be delivered at a highly predictable time with an overall low latency and jitter while being forwarded. Such applications in Automotive include sensors as a source for control loops performing operations on, for example, safety-critical vehicle functions. These can be scheduled by using the Automotive Ethernet protocol with the TSN standard.

The TAS, covered in IEEE 802.1Qbv - *Enhancements for Scheduled Traffic*, facilitates scheduling of such traffic while adhering to the requirements defined by Pannell (2013). These requirements, captured in Table 2.1, will be referred to describing the TAS standard, subject of this thesis.

Traffic Class	Max. Frame Size	Min. Frame Interval	Max. End-to-End Delay
Class CDT	128 [bytes]	500 [μs]	100 [μs/5 hops]
Class A	256 [bytes]	125 [μs]	2 [ms/7 hops]
Class B	256 [bytes]	250 [μs]	50 [ms/7 hops]
Class BE	256 [bytes]	N.A.	N.A.

Table 2.1: TSN Attributes [16]

Time-Aware Shaper

Within this section specifics of TAS will be presented. This is done by means of an example in which the TAS is introduced being implemented within a network switch.

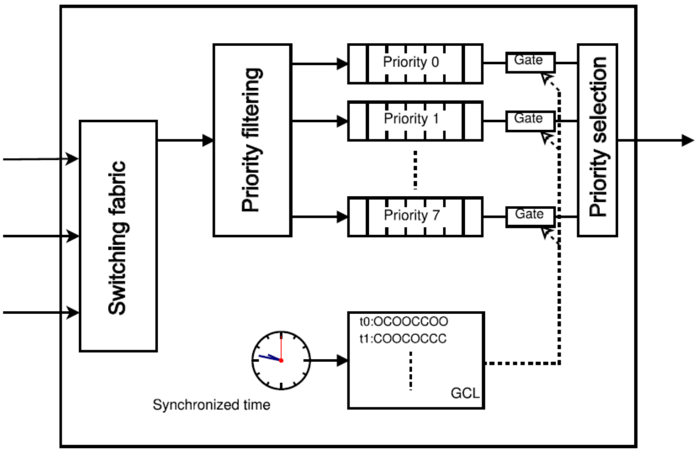

Figure 2.2: Network Switch supporting 802.1Qbv [13]

From Figure 2.2 the layout of the switch can be seen, being equipped with three ingress ports and one egress port. At the arrival of the data streams, the traffic is first being filtered by a switching fabric after which, according to the sub-standard used, the data is forwarded through the priority filtering mechanism to one of the eight respective queues. The data frames are stored in the queue assigned to their priority value and are to be forwarded in order of first-in first-out.

The pre-configured GCL coordinates actuation of the traffic gates. In case one or multiple are opened, the data frames are allowed to be forwarded towards the physical layer. The Priority Selection mechanism administers the specific forwarding order based on the frame priority. This to ensure, in case of multiple gates being opened, to adhere to the priority forwarding order.

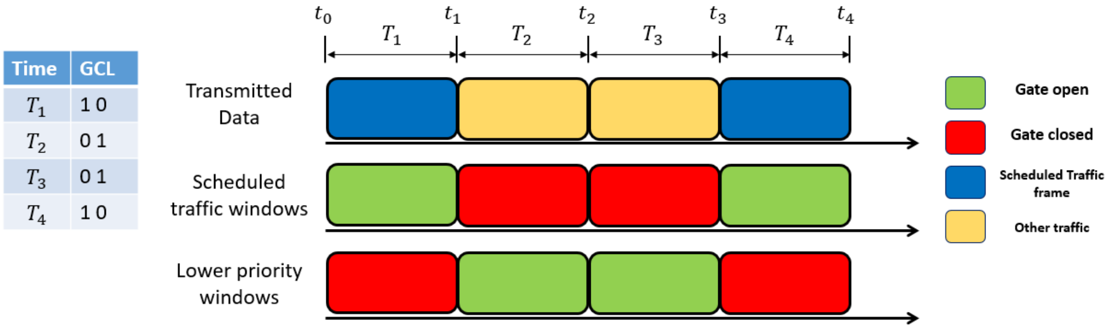

Figure 2.3: TAS Scheduling Example

From Figure 2.3 an example of scheduled forwarding on the physical bus can be seen. Opening times, denoted by a 1 in the GCL table, indicate at which times the gate per traffic class has opened to forward its accompanying data.
As forwarding of the scheduled traffic is to be guaranteed, before the start of each scheduled traffic window a slot reserving bandwidth is placed, assuring transmission of high priority at its desired time.

Guard Band

The bandwidth reservation described is called a Guard Band, present before the start of each scheduled traffic window.
According to [8], imprecise scheduling of data frames in the TAS may cause multiple sets of different traffic classes to have access to the network. Since this may influence the performance guarantees of the scheduled traffic, CDT, in terms of for instance latency and package loss, one must establish a protected channel.
It is advised to make use of the implementation of a Guard Band ensuring to protect the lower priority traffic from interfering with the activation time of the CDT slot.

Standard IEEE802.1Qbv suggests to define the Guard Band such that it reserves time equal to the duration of the largest Automotive Ethernet frame possible, being 298 [bytes] for BE and 322 [bytes] for AVB traffic [8].

Chapter 3

Gap Analysis

At the present time, the TSN standard for Automotive Ethernet comprises various sub-standards introducing its promising capabilities. Implementation in production vehicles is, however, beyond the bounds of possibility due to the hardware and software being absent.
For this reason, a gap analysis is being performed formulating the deficiencies to establish an In-Vehicle Network (IVN) comprising Automotive Ethernet with TSN.

This chapter is divided into three parts. First, the current state of communication busses in Automotive will be assessed. This includes the availability of the Automotive Ethernet sub-standards present enabling forwarding with real-time guarantees.
Next, the future state is examined, in which the bandwidth demands for ADAS become important. Finally, the gap to bridge between the current and the future state is presented.

3.1 Automotive Communication

The current state of Automotive communication busses encompasses all the information present at this time. It includes the reason why Automotive Ethernet should be implemented and the capabilities of the different sub-standards. The advantages include scheduling mechanisms, solutions gaining redundancy, least interference message forwarding and timing synchronization of all network systems.

Up to now, former research performed on Automotive Ethernet has tended to focus on worst case analysis of safety critical data as well as the implementation of various scheduling mechanisms, presented in literature by [2][4][20].

Implementation of TSN is, at this moment, impractical due to the absence of the set of applications realizing the written sub-standards. Various approaches have been used to mimic the standard under investigation, leaving the method of implementation to be interpreted by the author, causing possible deviations examining equal architectures.

Automotive Communication Busses

In current Automotive, communication busses such as CAN, Local Interconnected Network (LIN), Media Oriented Systems Transport (MOST) and FlexRay provide a connection between sensors, control units and actuators. Performing research on these individual busses one may find a different area of implementation of all available protocols leading to different domains of an IVN.
These domains and its concurrent communication busses are:

- **CAN:** Powertrain system
- **LIN:** Body Control

- **MOST:** Infotainment system
- **FlexRay:** Brake system

As many control units have to communicate with each other, and due to the different protocols used, gateways are necessary to translate the data being forwarded, introducing latency issues. Furthermore, implementing multiple gateways and the wiring harnesses associated with each communication bus, increases the costs and raises the vehicle weight.
With the rise of vehicle components tended to enable Autonomous driving, being for example High-Definition (HD) cameras and LIDAR, the data rates and overall bandwidth also need to increase, yielding a challenge for present communication busses.

Since costs during development and manufacturing of a vehicle are of importance and, for example, the domain of Body Control does not need to operate under the same requirements as the Brake system, these various communication busses are still implemented per domain. Yet, the approach of the IVN needs to change in terms of both, topology and underlying technology, to prepare for near future capabilities within Automotive.

Automotive Ethernet is a communication bus being developed providing a common protocol increasing data rates and bandwidth while decreasing the need for multiple gateways. As a result, only a single network will be available as the IVN, reaching higher speeds with an extremely low latency [1].

Available sub-standards

The present research explores forwarding of Time Critical Data over the Automotive Ethernet communication bus for which the TSN standard has been developed.
For the reason of safety-critical communication bus features the TSN working group has been initiated, assuring forwarding of a substantial amount of data within a restricted time duration. Along with the already available specifications introduced in AVB, various other specifications have been created, enabling timing guarantees for safety-critical traffic [19]:

- IEEE 802.1Qbv; *Enhancements for Scheduled Traffic*
- IEEE 802.1Qbu; *Frame Preemption*
- IEEE 802.1Qch; *Cyclic Queueing and Forwarding*
- IEEE 802.1AS-REV; *Enhanced Generic Precise Timing Protocol*

All the sub-standards listed have been examined to uncover the current condition of the standard. From related research investigating the different type of schedulers the TAS, covered in IEEE802.1Qbv, offers the best low-latency and jitter performance, compared to the Peristaltic Shaper, IEEE802.1Qch [20]. For this reason, and the implementation of Frame Preemption (IEEE802.1Qcc) only being possible once having selected a scheduler, the TAS is chosen to explore further.

Hardware/Software TAS

The current state of the TAS is the confined standard being present and related research performed on the comparison of different traffic shapers, supported by its worst-case analysis.
In terms of implementation of the standard, in hardware or software, even less is available.

Semi-conductor manufacturers such as NXP, Broadcom and Analog Devices supply microchips providing the capabilities to develop a TSN network as well as primitive evaluation boards, leaving narrow space for the researcher to adapt or implement the written standard in code or to evaluate it varying simulation parameters.

The current implementation of TAS, along some other TSN sub-standards present, have been examined on the TSN evaluation board from Analog Devices.
Through a webserver only limited parameters could be set such as, message size from the second stream and on, activation times through the GCL and the forwarding order.
Opposed to what is presented by Pannell (2013) in Table 2.1, Analog Devices only allows forwarding of the standard Ethernet Frame size, approximately 1522 [bytes] [7]. Moreover, the implementation of the Guard Band is set to only use the 'Fixed' Guard Band instead of the option to set the Guard Band according to the configured message size.
In conclusion, the provided evaluation board does not contribute to verify the TAS fully.

Other evaluation boards present from SoCe, *MTSN Kit*, and NXP, *LS1028A*, provide similar or even less capabilities configuring the TAS.
Software stacks are neither available, to be implemented on dedicated hardware, leaving a full verification of the standard impracticable.

In summary:

1. The general concept of the TAS becomes evident within the standard, IEEE802.1Qbv, a detailed implementation of it is missing allowing misinterpretation to the reader.
2. Verification of the TAS standard is only possible by means of evaluation boards with limiting possibility in configuration changes, leaving the promising features unproved:
    (a) Schedulability of a task set with scheduled traffic.
    (b) Influence of a Guard Band on the bandwidth utilization.
3. Currently, no commonly accepted software stack is available implementing the TAS.

3.2 Future Automotive

Ideally, within the future state the points summarized in the previous section have been completed. This would enable implementation of the TAS standard by developers to be verified or used in near future Automotive.

TAS in Autonomous vehicles

The necessity of a change in the vehicle network topology raises from the introduction of, for example, autonomous driving. This type of driving requires the vehicle to sense and act equal to a certified driver.
Various components are added to the vehicle to enable autonomous driving such as cameras and RADAR/LIDAR sensors, all transmitting data to a control unit for means of processing and actuation accordingly. Bandwidth demands for such sensors as well as transmission of imaging sensing data range from 10 [Mbps] up to 1 [Gbps], demands which cannot be reached with communication protocols currently applied [1].

The Automotive Ethernet bus is capable of operating at these high bandwidths for which only traffic shapers are necessary guaranteeing data to arrive in time at its destination. Together with the AVB standard, TSN provides the TAS standard guaranteeing arrival of critical data within microsecond precision. As the TAS is capable of forwarding not only time critical data but also multimedia streams along with best-effort traffic, this standard is suited to fulfill the requirements for autonomous driving.

As per example Volvo Cars is limiting their vehicle speed in 2020 to 180 [km/h], full autonomous driving at this speed with a measured accuracy of 1 [cm] would result in a sampling period of 200 [μs] [1]. Data forwarding rates of this order can never be reached using one of the conventional

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[1] Calculation can be found from Appendix A.1

communication busses, it is, however, still to be verified if Automotive Ethernet can gain such rates.

Evaluation

As in automotive commonly the rate and size of the data to be forwarded on the bus are known to have a accurately working vehicle function, optimally, scheduling of the data task set could be verified before implementation on the network.

Research to date has only determined, in a mathematical way, the schedulability of a pre-defined task set, even without including the bandwidth reservation before each scheduled traffic slot, called a Guard Band. It is moreover still unknown what the influence of the Guard Band is on the schedulability and the percentage of bandwidth utilization being reserved. Preferably, this is included in any tool simulating the task set to be scheduled on the IVN.

3.3 Gap description

The gaps identified within this section feature the improvements necessary to enable Future Automotive, based upon the current position. Gaps presented are listed in order of priority from the perspective of the automotive industry.

As some gaps are not possible to be fixed by the graduate, caused by limitations in agreements from the industry and time-span of this thesis, the scope of the research has been restricted to the information currently available.

TSN standard

A general observation, for all the sub-standards examined, is that the information available is limited to an informative section describing the operation of the standard and entitling its objectives. Rather, an in depth description supported by various use-cases, agreed upon by a board of automotive manufacturers, would suffice.

Implementations

Part of the TSN standard is implemented through hardware, supported by settings configured by the user through software. The manufacturers of Automotive hardware/software depend on the information supplied to them, in this case the level of detail present in the corresponding standard.

As a result from the inadequately described TSN standard, the development of hardware and software hinders, leading to a suspension of the implementation on Automotive Ethernet.

Evaluation

With the TSN standard being only partly available, leading to a delay in the development of hardware and software, the evaluation of the standards becomes challenging as well.

As evaluation of the TAS standard is indicated as a gap, the scope of this thesis is narrowed to verify the schedulability of a task set and the influence of a Guard Band on the bandwidth utilization.

Method

In the introduction to this chapter the gaps identified as superior comprise the revision of the TSN- and accordingly TAS standard, ensuing any standardized hardware or software stack.

To contribute to the development of the TAS standard, to verify schedulability of a task set and to assess the influence of the Guard Band, a software model will be constructed in MATLAB/Simulink, resolving a part of the gaps indicated.

3.4 Conclusion

Although the current study is based on a small sample of the Automotive Ethernet standards, the findings suggest that the available TAS standard requires further development prior to implementation.

As this also limits the development of hardware and software, resembling the written standards, it is not expected that Automotive Ethernet will be implemented in production vehicles any time soon.

Since the schedulability currently can only be examined using mathematical methods, a software model resembling the internals of a TSN switch would already contribute to the development of the standard. This is done such that the capabilities of the TAS can be verified.
In addition, examining the influence of the Guard Band has not been performed to date, leaving possibly room for an increase in the percentage of bandwidth being utilized.

Chapter 4

Time-Aware Shaper

As the remaining part of this thesis will focus on the scheduling mechanism Time-Aware Shaper, in depth information is presented on the possible implementations of the different Guard Band approaches and their advantages.

Of particular concern is the schedulability of a task set and the influence of the Guard Band on the total bandwidth utilization, as indicated in Chapter 3.

4.1 Schedulability

Before being able of implementing and subsequently analyzing the influence of parameter changes or different approaches of a Guard Band, one must be assured that the task set allocated can be scheduled.
Research on the parameters influencing the schedulability of a task set are centralized around the message requirements stated in Table 2.1, here the payload size and generation period are defined to achieve the latency guarantees to be reached per traffic class.
Schedulability is achieved if the amount of messages generated for scheduled traffic is equal to the amount of messages being forwarded on the communication bus.

4.2 Guard Band

As described in Chapter 3, the task set is often verified to be schedulable before implementation on the vehicle, making the Guard Band redundant. This condition would hold in a theoretical environment, as is resembled within the simulation model under development.
Nevertheless, the possible addition of multiple traffic streams, being forwarded by various nodes coupled to the system, may cause interference leading to jitter, which prevent data frames from being forwarded at activation time, jeopardizing the timely forwarding of scheduled traffic. The necessity of a Guard Band is thus evidenced by the fact that the activation time of the scheduled traffic slot, CDT, is to be guaranteed.
The approach proposed by the TAS standard on the other hand leaves room for improvement, causing a considerable percentage of the bandwidth utilization to be reserved.

Fixed Guard Band

The approach proposed within IEEE802.1Qbv describes the Guard Band to be a maximum-sized Ethernet frame, being according to the configuration requirements in Table 2.1, 298 [bytes]/23.84 [μs] for BE traffic and 322 [bytes]/24.76 [μs] for AVB, at a data link rate of 100 [Mbps].
This is what during research has been named as Fixed Guard Band being applied before the activation of each protected data flow, as presented in Figure 4.1 and illustrated in Figure 4.2.

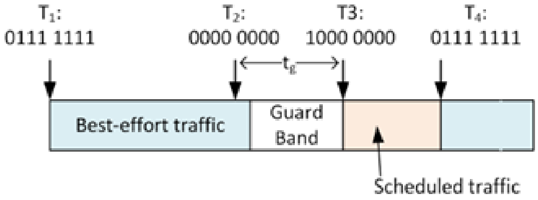


Figure 4.1: Implementation Guard Band [6]

As in cases where the maximum bandwidth utilization is required, transmitting for example data of X-by-wire systems, multiple camera/LIDAR/RADAR feeds, multimedia streams and status information regarding comfort functions, the addition of a Fixed Guard Band limits the promising capabilities of Automotive Ethernet.
For this reason, alternatives have been examined presented within the upcoming sections.

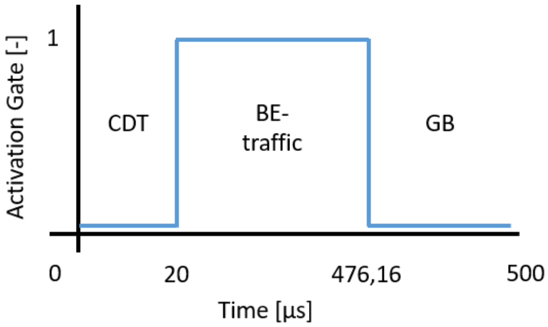


Figure 4.2: Fixed Guard Band

Variable Guard Band

The IEEE802.1Qbv standard implies the application of a Guard Band having a variable starting time. The result would be that additional lower priority data can be scheduled utilizing an higher percentage of the communication bus.

As noted by Maxim and Song (2017), the size of the Guard Band is equal to the largest frame available within the task set, among AVB and BE traffic, illustrated in Figure 4.3.
Reflecting on this implementation, as a Variable Guard Band, this method will only leverage in case frames of less than maximum size are being forwarded.

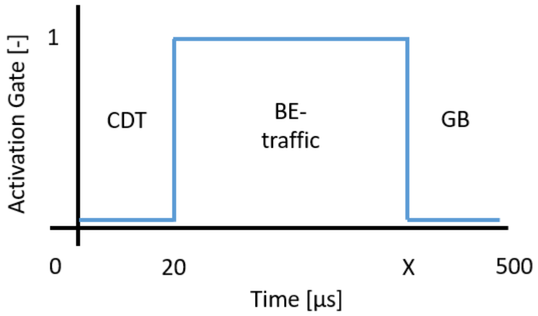


Figure 4.3: Variable Guard Band

Since the user defines the maximum allowed size of payload sent within a frame, this method might result in the desired effect, reaching an increased percentage of bandwidth utilization.

Dynamic Guard Band

Another approach, derived from the previous implementation of the Variable Guard band, is the so called Dynamic Guard Band.
In this case, the size of the pending message in the lower priority buffer is monitored to be, normally, forwarded at the upcoming opening of the gate. Instead, the time remaining to the activation of the CDT slot is compared to the duration of the pending message and, if less, forwarded during the Guard Band period, as is illustrated in Figure 4.4.
By implementing this approach an increased bandwidth utilization might be reached, depending on the configuration set by the user, varying the activation time of the Guard Band dynamically based on the lower priority message present in the buffer.

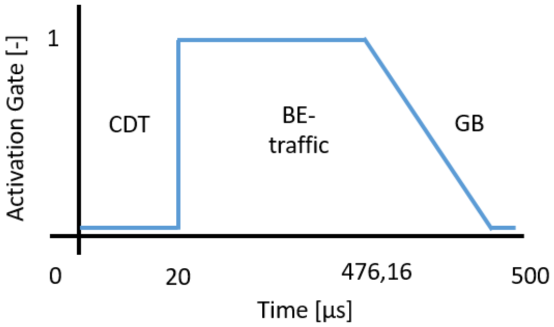


Figure 4.4: Dynamic Guard Band

This would result in forwarding of data opposed to the method presented in Figure 4.5 as indicated by IEEE 802.1Qbv.

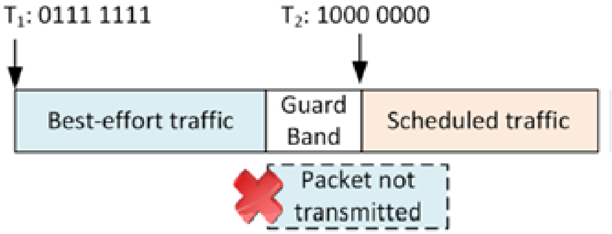


Figure 4.5: Forwarding within Guard Band period [6]

Number of Guard Bands

An approach, independent on the size of the Guard Band, to reach an higher percentage of bandwidth utilization has been examined by Dürr and Nayak (2016).
Based upon a methodology originally introduced as *Job Shop Scheduling Problem*, Dürr and Nayak (2016) have adapted the technique to optimize the scheduling of data frames onto the network and accordingly number of activation's of the gates, called No-Wait Packet Scheduling Problem (NW-PSP).

By using a Tabu search algorithm the flow-span can be minimized which leads to a near-optimal solution for scheduling of data frames. The addition of a compression algorithm, reducing the number of gate instances, an average reduction in bandwidth utilization of 24 [%] is reached.

As the focus of this thesis lies on the reduction of the size of the Guard Band and an application proving TSNs schedulability, implementing this approach is out of scope.
Eventually, a combination of both methods might lead to an noteworthy effectively usable bandwidth percentage which might be worth to be subject of future work.

4.3 Conclusion

Expected is that the schedulability is guaranteed, adhering to the requirements presented in Table 2.1.
The various approaches for implementation of the Guard Band, present in the TAS standard and proposed to it, are introduced with the intention to maximize the lower priority traffic to be forwarded.

As the, so called, Fixed Guard Band will reserve an equal time slot irrespective of the user configuration, the Variable- and Dynamic Guard Band are proposed to behave opposite.
Shortened bandwidth reservation, while scheduling a task set with less than maximum sized Ethernet frames, is expected to be allowed assuring forwarding completion before the transmission of scheduled traffic.

Scheduling large data-sets with various priorities is not addressed within this study. The optimization algorithm presented to decrease the number of Guard Bands could however be beneficial once TAS is to be implemented in future work.

Within the upcoming chapter the development of the simulation model will be presented with which the schedulability and approach of the different Guard Bands may be examined.

Chapter 5

Simulation Model

Part of the aim of this study is to develop software in which the TAS, as specified in IEEE 802.1Qbv, is being modeled in order to simulate and concurrently analyse the results. Simulation, using the TAS, must prove the schedulability of a task set and illustrate the influence of the various approaches of the Guard Band.
The application has been developed according to the switch internals presented in Chapter 2, Figure 2.2.

As, at the time of writing, no simulation tools exist to monitor the TAS, a model has been created using MATLAB/Simulink.

5.1 User-Configuration

The intention of the scheduling application is to allow a user to configure a system conform the sub-standard *IEEE 802.1Qcc - Central Configuration Method.*
For the purpose of configuration, a Graphical User Interface (GUI) has been created in which the user may set various parameters resembling an Automotive network system of interest. Figure 5.1 presents the GUI, allowing the user to configure a task set to be forwarded and later analyzed using the TAS.

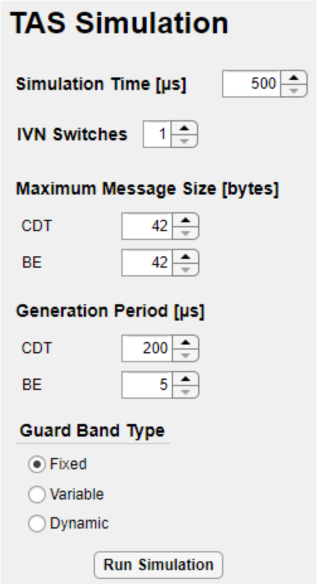
Simulation Time

The simulation time can be set according to the desired duration, resembling an Automotive driving scenario.
The frame interval of CDT can be set equal to the requirements stated by Pannell (2013), as presented in Table 2.1 which should be at a minimum of 500 [μs] to meet the end-to-end latency guarantees. For this reason, multiples of the minimum frame interval are chosen to be configured by the user to be used as the simulation time.

IVN Switches

The setting in which the amount of switches within the network is determined, defines the duration of the traffic slots present. This, again, is related to the requirements stated by Pannell (2013), where the end-to-end latency guarantee declares to be 100 [μs]/ 5 hops.
Reverting this to the latency guarantee per hop for CDT traffic, each hop and thus accordingly CDT slot, must enable arrival of data at its destination within less than or equal to 20 [μs] per hop.

The user configures the entire IVN according to IEEE802.1Qcc. All components coupled to this IVN are synchronized in time, using IEEE802.1AS-REV. The addition of a switch to the network,



TAS Simulation

Simulation Time [μs] 500

IVN Switches 1

Maximum Message Size [bytes]

CDT 42

BE 42

Generation Period [μs]

CDT 200

BE 5

Guard Band Type

● Fixed

○ Variable

○ Dynamic

Figure 5.1: TAS User Configuration Pane

with a maximum of 5, will thus increase the CDT slot with 20 [μs]. This, however, decreases the amount of lower priority traffic which can be forwarded.

The number of switches to which the duration of the slots can be adapted ranges from 1 up to and including 5, adhering to the latency requirements for CDT as is stated in Table 2.1.

Maximum Message Size

As the size of the messages is related to the duration and priority of the slot, a maximum message size has been established for which the requirements can be met.

For CDT traffic this encompasses a maximum of 128 [bytes] , to which the standard TSN Ethernet header is added of 42 [bytes], reaching a size of 170 [bytes] in total to be forwarded [16][20]. The minimum size payload has also been specified to be 42 [bytes] , in which the minimum size of CDT to be forwarded is 84 [bytes] [20].

As for the BE traffic no requirements in terms of latency have been specified, as well as the less stringent requirements for AVB traffic, the maximum allowable payload sizes have doubled, compared to CDT, being a maximum payload size of 256 [bytes].
Each BE message receives an additional header of 42 [bytes], where the header of AVB is 66 [bytes] due to the inclusion of the Audio Video Transport Protocol (AVTP).

Generation Period

The message generation period comprises the duration in time in which new messages arrive at the switch and subsequently being forwarded to the physical layer.
As the requirements for CDT in Table 2.1 of Chapter 2 present, the guarantees are most likely to be met in case data arrives every 500 [μs].

Vehicle manufacturer Volvo recently announced to restrict their speed limit in 2020 to 180 [km/h], expecting the number of casualties to decrease [10].
To assess the ability to perform autonomous driving at these velocities, the capability of data forwarding by the ADAS at such high rates using the TAS is to be evaluated. The essential

generation period for CDT has thus been calculated to be 200 [μs], considering a 1 [cm] accuracy [1].

To assess both conditions, the user may vary the data generation period for CDT between 200 and 500 [μs] with a step-size of 100 [μs].

For BE traffic, no such specifications are present and might arise more often, certainly as an addition to the higher priority AVB traffic.
The values chosen for the user to be configured, facilitate the possibility to verify the influence of any lower priority data on the schedulability, and utilization of the Automotive Ethernet communication bus, especially in terms of the applicable Guard Band.

The generation period for BE traffic can be set in a range of 20 - 200 [μs] with an increment of 10 [μs].

Guard Band Type

To examine the influence of the different approaches as presented in Chapter 4, opted by IEEE 802.1Qbv and as a proposal to the TSN sub-standard, one may choose from the options present in the section of the Guard Band type.

5.2 Support File

The settings, configured by the user, are directed to the simulation model through a MATLAB .m-file. Depending on these settings, signals such as actuation of the GCL and control of the Guard Band are established after which the data produced will be analysed.
The first part of the system configuration creates the slot sizes and GCL signal.

Gate Signal & Slot Size

The slot size of the respective traffic classes controls the opening and closure of the gate, enabling forwarding of data at its allocated time. To create the signal with which the gates are being controlled, the user settings must be observed since various parameters may influence the shape of the signal.

Since the objective of this thesis concerns the schedulability and utilization of the communication bus it is assumed that high priority traffic, CDT, is always present in the task set and has to be scheduled first, followed by lower priority, BE traffic. This is illustrated in Figure 5.2 used to establish the GCL signal.
Initially, the yet present parameters are received, encompassing the start and end of the CDT slot, start of the BE slot and end of the Guard Band.

As the different approaches of the Guard Band, which can be selected by the user in the GUI, result in a shift of when the BE traffic slot ends, an *if-else* statement validates the approach chosen and accordingly sets the variables *beEnd/gbStart*.
The *if-else* statement indicates a distinction is made between two approaches, although three approaches are being present. Either the approach of the Fixed Guard Band can be selected or any other approach. As presented in Chapter 4, the Variable Guard Band is set using the duration in time of the maximum size low priority traffic. This approach is also the foundation of the proposed Dynamic Guard Band, ensuring an improvement of bandwidth utilization opposed to the Fixed Guard Band in case the requirements for the Dynamic approach can not be met.

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[1] Calculation present within Appendix A.1

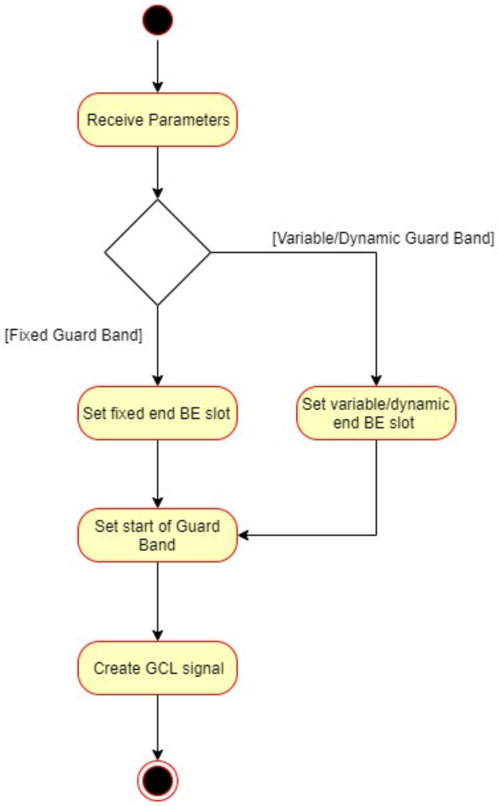

Figure 5.2: Activity Diagram; Formation GCL Signal/ Traffic Slot Size

At this point, all parameters to form the control signal for the CDT and BE gates are known and can be generated.
Depending on the overall simulation time this signal is being repeated and loaded in to a scenario to be used in a *Signal Editor* block in Simulink, which will be elaborated on in the section describing the GCL.

5.3 Simulink Model

The simulation model is created in Simulink, using the SimEvents toolbox to design part of the Automotive Ethernet communication bus resembling the Time-Aware Shaper of the TSN standard. SimEvents enables assessing the influences of parameter changes on timing, message forwarding and bus utilization.
Figure 5.3 illustrates the simulation model implementing the TAS in the form of a block definition diagram.

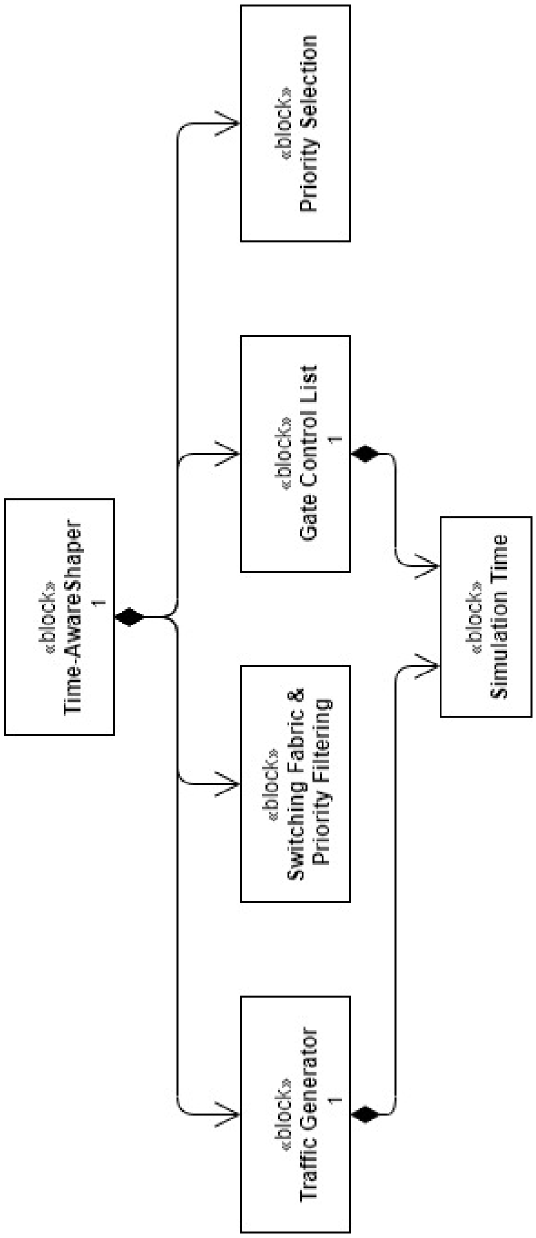

Figure 5.3: Block Definition Diagram; Simulation Model

Traffic Generator

The traffic generator, on the left in Figure 5.3, creates arbitrary messages with a maximum size and period configured by the user.

From Figure 5.4 the operation of the traffic generator can be seen, which resembles an input of CDT and BE traffic data being received from, for example, two different transmitting ECUs within the IVN.

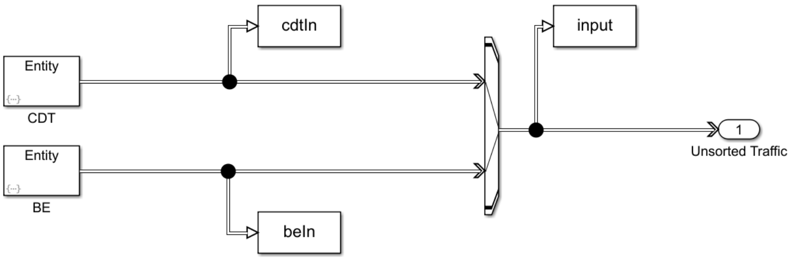

Figure 5.4: Detailed view: Traffic Generator

The Entity Generator blocks, labeled CDT and BE, create message frames containing the fields, *Size*, *Priority*, *Timestamp* and *Duration*. Upon generation, the message size, of which the maximum is configured by the user, and a timestamp are added to the frame, as presented in Figure 5.5:

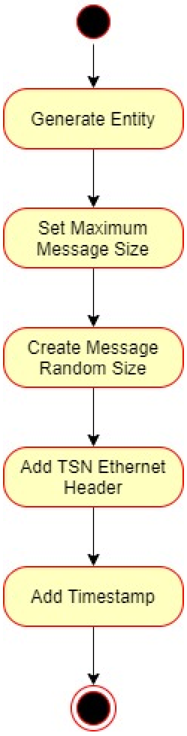

Figure 5.5: Activity Diagram; Frame Generation

The variable *Timestamp*, is being added from a Simulink function monitoring and providing the time to the entities at the time of generation, arrival at the egress port of the switch and entry of the upcoming switch or end station.
Figure 5.6 presents the internals of the *currentTime* function, comprising a digital clock assessing

the simulation time which is being forwarded as an output of the function, variable y, and as an output to serve the GCL sub-system.

Once the entities are generated these are forwarded to an input switch where they are placed on a central communication bus as unsorted traffic.
The software blocks coupled to the connections between the individual components, *cdtIn*, *beIn* and *input*, serve the purpose of data forwarding to the MATLAB workspace for further analysis.

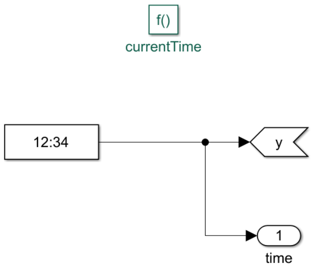

Figure 5.6: Detailed view: Current Simulation time

Switching Fabric & Priority Filtering

The unsorted traffic is forwarded and received within the *Switching Fabric* & *Priority Filtering* system. From Figure 5.7, a detailed view is shown in which the components, accomplishing the functionality of the sub-model, are presented.

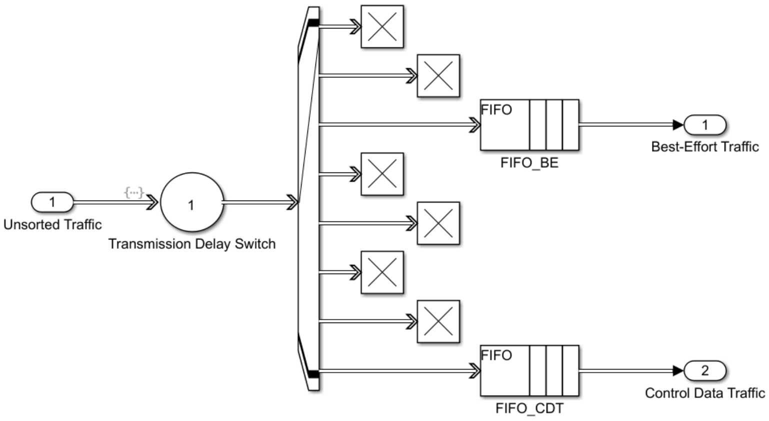

Figure 5.7: Detailed view: Priority Filtering

After receiving the unsorted traffic it passes through an Entity Server resembling the processing time of the Automotive Ethernet switch. While simulating, only one message frame can be present within the Entity Server and will only be forwarded after 4.6 [μs], indicated as the transmission delay of the switch, presented by Steinhammer et. al (2006).
Experiments have proved that the transmission delay measured on a Time-Triggered Ethernet (TTE) switch, reasonably similar to switches for the method under investigation, are constant and independent of the load experienced by the network [5].
While passing through the Entity Server, the frame size is being verified and assigned to the variable *Duration*, present within each entity. The duration of each frame is being used within the sub-system *Priority Selection*. Calculation of the frame duration is performed for a communication bus operating at 100 [Mbit/s], as can be seen from Figure 5.8:

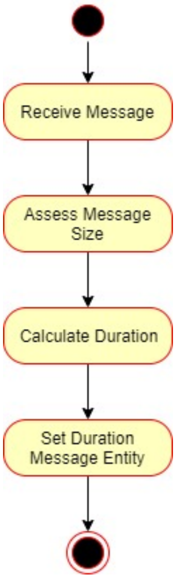

Figure 5.8: Activity Diagram; Assessment Frame Duration

Once forwarded from the Entity Server, the entities arrive at an output switch directing the frames to its corresponding First-In First Out (FIFO) buffer. Forwarding to the correct buffer is based upon the field value, *Priority*, assigned to the entity at generation time.
As BE traffic has the lowest priority, *3*, this is forwarded to the buffer coupled to the third port of the output switch, equal to CDT, assigned with a priority of *8*. Within the buffer, messages are being stored and forwarded in the order *First-In First-Out*, based on configuration of the GCL which will be explained in the next paragraph.

As the intention of the thesis is to examine the influence of the user settings on the task schedulability and utilization, mainly caused by the different approaches of the Guard Band, only one queue of BE traffic is utilized. Adding multiple BE-traffic streams or AVB traffic to the simulation will not increase the number of Guard Bands present. Moreover, it would cause the simulation model to become unnecessary complex without adding any value in terms of examining schedulability or bandwidth utilization reserved by the Guard Band.
Furthermore, as described within the introduction of this chapter, AVB traffic has not been taken into account due to the implementation of a different type of shaping algorithm, Credit-Based Shaper (CBS).

Gate Control List

The GCL controls forwarding of the message frames present in both buffers, based on the user settings, as can be seen from Figure 5.9.

Message frames may only leave the buffer if the devoted Entity Gate has opened.
In case of CDT, each simulation period starts with forwarding of this highest priority traffic, the block signal created from the user configuration sends an opening command to the *activationCDT* block after which the gate will open or close for the specified amount of time.

Forwarding of BE traffic is not that straightforward and depends on some more parameters.
Once selected one of the approaches present in IEEE 802.1Qbv, the Fixed- or Variable Guard Band, the activation times of the BE traffic as well as the Guard Band can be determined at the start of the simulation.
In case the proposed procedure is being selected, the Dynamic Guard Band, the activation of

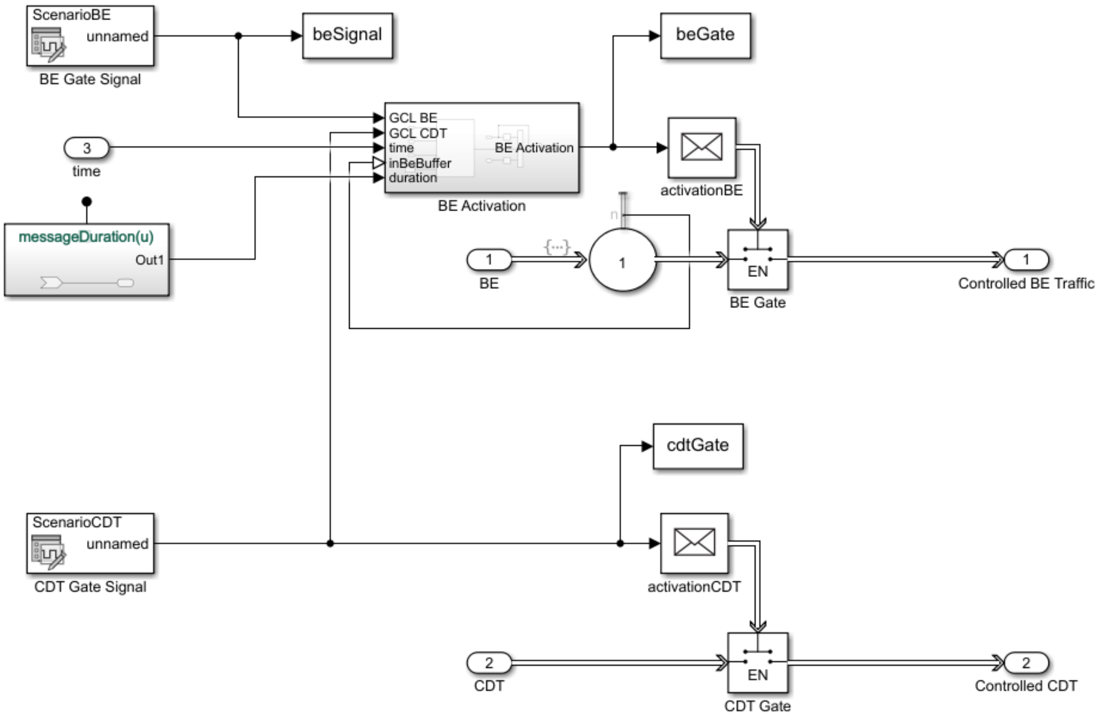

Figure 5.9: Detailed view: GCL

the Guard Band and end of the BE slot must be determined at run-time. For this reason, more software blocks are required in the upper half while controlling forwarding of BE traffic.

The approach of the Dynamic Guard Band is only beneficial in case message frames are present within the buffer. While using the provided FIFO-buffer, this data is not present to the user at run-time. For this reason an Entity Server has been added, with a service time of 0 [μs] and a capacity of 1 frame, to resemble an extension of the BE buffer for reasons of analysis.
In case the generation period of BE is chosen such that frames are being generated at a long time interval, it might occur that the buffer holds no data and there is no need to continue execution of the calculations for the Dynamic Guard Band. This variable, *inBeBuffer*, serves thus as an input for the dynamic activation time of the Guard Band, along with the current simulation time, *time*, message duration, *duration*, and the gate signals, *GCL BE* and *GCL CDT*, but only if data is present within the buffer.

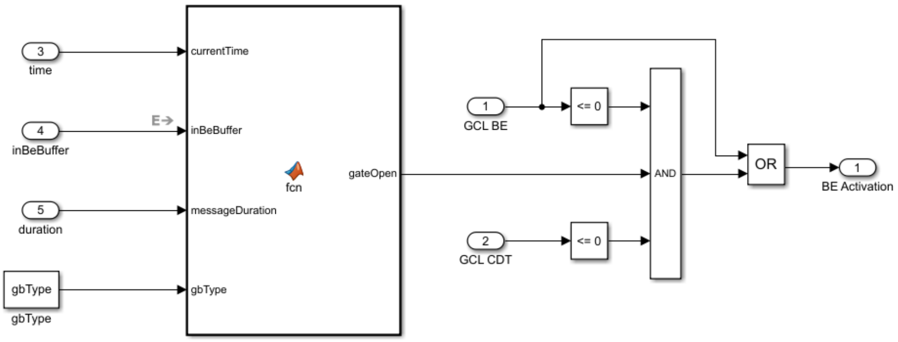

Figure 5.10: Detailed view: Activation BE traffic

From Figure 5.10 the inputs to the function can be seen, after which the activation signal is forwarded and compared to verify which is to be used controlling the BE traffic gate.

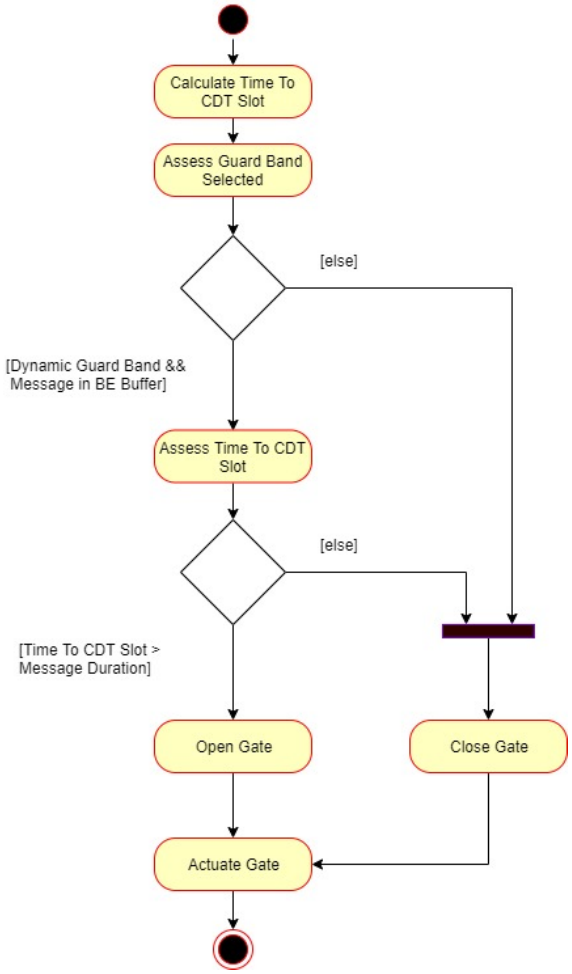

Figure 5.11: Activity Diagram; Gate Actuation

The activation of the gate, either to serve for a Dynamic, Variable or Fixed Guard Band, can be seen from Figure 5.11.
At the start of the function the time to the next CDT slot is being calculated. Accordingly, a verification is performed to examine the Guard Band type selected in the GUI, and the presence of a message in the buffer. In case all conditions hold, the time to the end of the slot being greater than the duration of the message present in the buffer, the gate is opened to forward a frame during the Guard Band period.

As the verification of the time to the end of the slot continues during simulation, it is compared to the CDT and BE gate signal. Only once the Guard Band is intended to be active, the Dynamic Guard Band may be applied to control the BE gate. This is accomplished using the block scheme on the right of Figure 5.10.

Priority Selection

The last phase of the TAS encompasses the *Priority Selection*, in which in case of multiple gate openings the highest priority traffic is allowed to be forwarded, followed by transmission of data in descending order of priority. This is controlled by the output switch, filtering on the variable *Priority*, member of each entity.

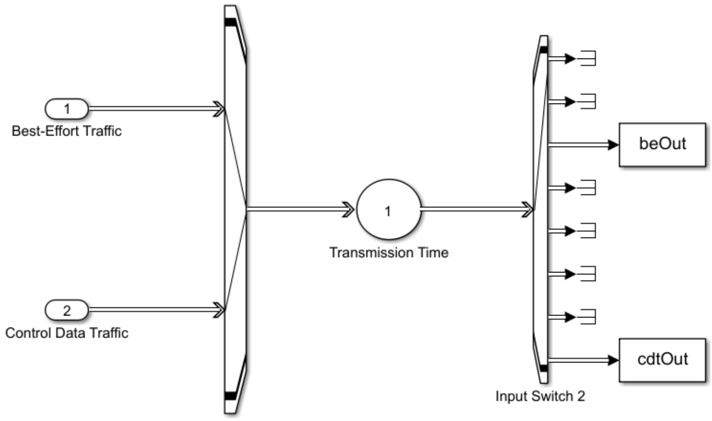

Figure 5.12: Detailed view: Priority Selection

As in related research, time is allocated to forward a message frame to the physical layer, mostly included in the transmission time to the next component. For this reason an Entity Server is added with a service time value based on the duration of the to be forwarded message, derived from the variable *Entity.Duration* as part of each frame, introduced in paragraph *Switching Fabric & Priority Filtering.*
The frames are being forwarded one-by-one to resemble an Automotive Ethernet switch with only one egress port to be scheduled traffic.
For purposes of analysis the end of the network consists of an output switch filtering on priority to verify the arrival times of the individual frames at its destination.

5.4 Simulation Procedure

The influence on schedulability and bandwidth utilization will be examined. This is done performing a, partially automated, parameter sweep on the simulation model, presented in Figure 5.3. During this simulation the message generation period will be varied after which the simulation will be repeated for different approaches of the Guard Band. Within all simulations the simulation time is set to an arbitrarily chosen period of 5000 [μs].

For purposes of analysis and comparison after simulation, the entities generated must be equal in size during different simulations, while varying the approach of the Guard Band.
As only the maximum size of the messages being forwarded can be set by the user and the generation is performed by the MATLAB function *randi*, this function must be examined in order to create equality during various simulations.

The MATLAB function, *randi*, has been used to create random integer numbers to resemble the payload size of a message within a user specified range. The sequence of these numbers produced is based on internal settings which can be altered using the MATLAB function *rng*.
From examining *rng*, one may find that there are numerous possibilities to generate a random number sequence, however, if these settings are left unaltered a default setting will be used in which each sequence of numbers being generated will behave as if the MATLAB program was restarted. The seed used to control the predictability of the numbers generated is in default mode set to 0, applying the Mersenne Twister number generator algorithm [15].

5.5 Simulation Expectations

Schedulability

First and far most important, the task set composed must be schedulable.
In case the size of the messages generated per traffic class exceeds the amount which can be possibly forwarded in a slot, the task set becomes not schedulable and there would be no reason to continue simulation.
The intention of the simulation is to visualize if a certain task set is schedulable and to present its corresponding settings. Results of this simulation could help the user while configuring the messages to be forwarded on the IVN.

Guard Band

From preliminary research the influence of the different approaches of the Guard Band is expected to be independent of:

- Simulation Time,
- Number of IVN switches, *and*
- Slot size[2]

Based on the approach selected, some parameters such as the message size and number of messages present in the queue may have influence on the type of Guard Band under investigation. These expectations will be discussed for each corresponding implementations.

---

[2] In terms of the duration of the Guard Band

Fixed Guard Band

Concluding from what is present in the IEEE 802.1Qbv standard, the implementation of the Fixed Guard Band, compared to the other approaches, is expected to be the least favorable option.
This opinion is supported by the fact that unlike the size of the low priority data present, either BE or AVB traffic, the approach reserves the maximum amount of time in terms of bandwidth which reduces the utilization of the communication bus.
An advantage of this approach is the determinism while assessing the schedulability and maximum data size to be forwarded in the slot.

Variable Guard Band

The expected improvement of the Variable Guard Band compared to the Fixed Guard Band may only be noticed while the to be forwarded messages of lower priority traffic, BE and/or AVB, are less than maximum sized payload frames. In any other case the approach of the Variable Guard Band is expected to behave equal to the Fixed Guard Band.

Dependent on:

- Message size[3]

Dynamic Guard Band

As the proposed implementation of the Dynamic Guard Band is based on the Variable Guard Band, the randomness during message generation is expected to determine the improvement of the schedulability and bandwidth utilization. In the worst case, the last message to be forwarded arrives too late to be forwarded, resulting in an equal behaviour as noticed within the Fixed Guard Band. As this may vary per iteration, this option is still expected to be in favor over the Fixed- and Variable Guard Band.
Expected is that with a large period time of generating low priority traffic, the buffer might become empty which results in no present messages to be forwarded during activation of the Guard Band, for this reason the Dynamic Guard Band is based upon the Variable Guard Band, being an advantage over the Fixed Guard Band, if payload generated is set to be less than a maximum sized Ethernet Frame.

Dependent on:

- Message size, *and*
- Messages in queue

5.6 Conclusion

As the model is developed in close relation to the TAS standard the promising capabilities must become evident during simulation. Ever since it leaves room for improvement the schedulability and influence of the Guard Band is expected to be visualized.
Improvement can be found in the addition of AVB and BE-traffic streams to complete the model. This will, however, not influence the results of the simulation as these streams are of no effect on the examination of schedulability and the Guard Band.

The expectations stated are based upon preliminary research, while validating the development of the simulation model according to the TAS standard.

---

[3] Only BE and/or AVB traffic

Chapter 6

Results & Discussion

The results in this chapter indicate that the expectations considering the implementation of the Guard Bands can be validated, supported by the evidence of schedulability of a task set according to the requirements stated in Table 2.1.
The next chapter, therefore, moves on to discuss the abilities to advance the current research and the deficiencies present within the current model.

6.1 Prove of schedulability

First and foremost important is to justify the schedulability of the CDT streams.
As presented in Chapter 3, the sampling period of extremely precise sensors providing information to enable autonomous driving is calculated to be in a range of 200 [μs], although the requirements in Table 2.1 state to be at a minimum of 500 [μs].

During the simulations a sweep has been performed on the generation period of CDT, ranging from 200 - 500 [μs], to verify the influence on the schedulability.
The results can be seen from Figure 6.1 and 6.2, representing both a non- and schedulable condition.

Information Figure

The information presented within the figures depicting the schedulability of the task set will be clarified within this textbox.

- X-axis: Time in [μs].
- Y-axis: Priority of datastream forwarded,
  7 - CDT, 3 - BE, 1/0 - Opening/Closing gate.
- Text boxes: Providing the simulation settings and utilization percentage of the communication bus.
- The black bars evident at the top of the figure represent the periodicity in which a new CDT message arrives.
- The rectangles present at index 7, in red, represent the CDT traffic being forwarded.
- The rectangles present at index 3, in green, represent the BE traffic being forwarded.
- At the bottom of each figure the activation of the BE gate can be seen,
  1 - Open, 0 - Closed.

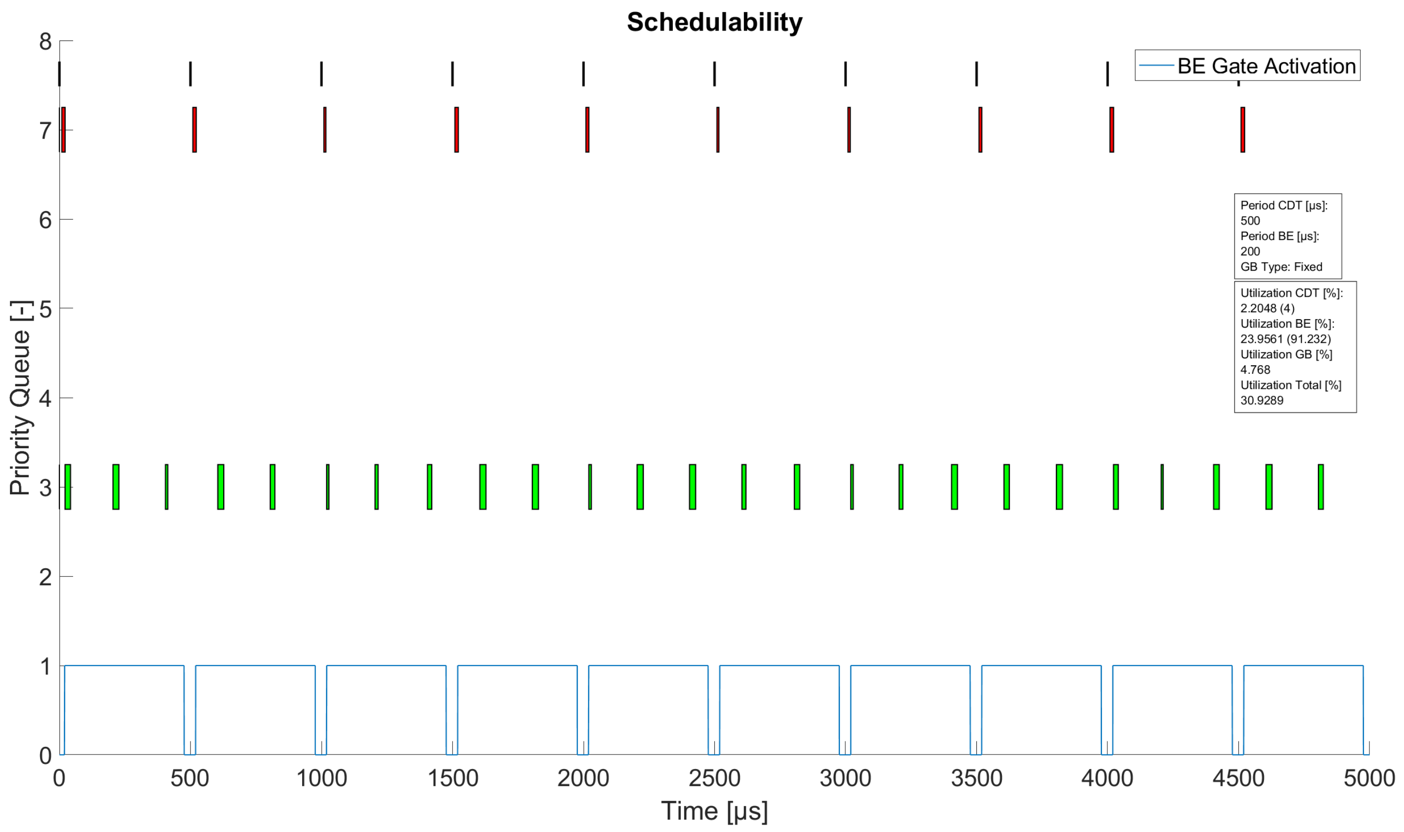

Figure 6.1: Schedulable configuration

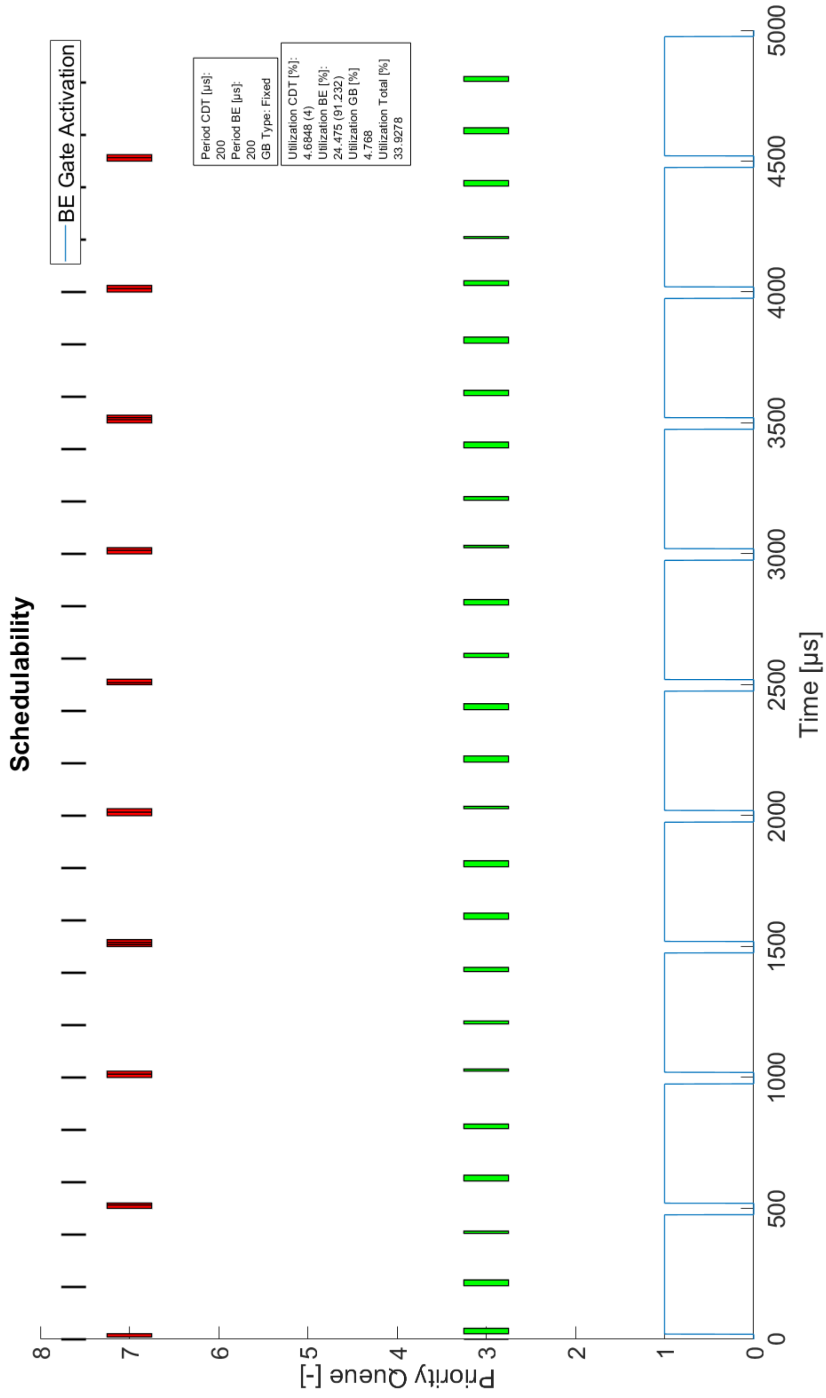

Figure 6.2: Non-Schedulable configuration

Figure 6.1 represents a schedulable configuration which can be concluded from the generation and accordingly forwarding period of the CDT traffic. The amount of CDT messages being generated, according to the requirements specified, are forwarded within the same simulation period, guaranteeing the frames to arrive within the latency bounds stated in Table 2.1.
Furthermore, the percentage of utilization from CDT is less than the maximum allowable traffic to be forwarded in the slot, demonstrated by the numbers under *Utilization CDT [%]* within the annotation in the figure.

Within Figure 6.2 a configuration can be seen which is not schedulable. From both, the percentage of utilization within CDT and the generation/forwarding period of data frames on the bus, a surplus can be seen. The result is a non-schedulable task set given that there are more messages being generated than may arrive within the strict latency requirements.
The non-schedulable task set is configured according to the calculation derived from the sampling period of extremely precise sampling for autonomous driving, 200 [μs]. Each increment up to a generation period of 500 [μs] for CDT leads to a non-schedulable configuration, given that the duration of the complete slot is left unaltered, respecting the requirements in Table 2.1.

In both configurations presented, the BE traffic is not being monitored in terms of schedulability. As the name implies, best-effort traffic is of less importance to arrive compared to CDT. It is, however, guaranteed that the BE traffic does not delay the higher priority traffic by, for example, forwarding on the communication bus while the BE gate has closed.

6.2 Guard Band

As the schedulability of the task set is being guaranteed, the influence of the different approaches of the Guard Band can now be verified, after having confirmed its implementation is correct.

Implementation

Chapter 4, Figures 4.1 and 4.5, introduced the limitations of message forwarding around the activation time of the Guard Band.
Messages which were being forwarded, finalizing transmission before the start of the CDT slot are allowed. Starting transmission at or within the Guard Band period is, until now, strictly prohibited.

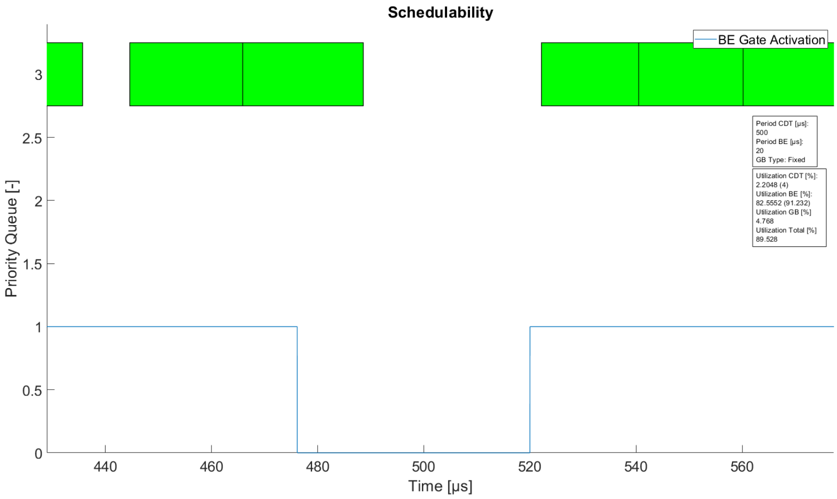

Figure 6.3: Forwarding during Guard Band

From Figure 6.3 the implementation can be seen for a configuration in which every 20 [μs] a new BE traffic message is being generated. The yet transmitting message is allowed to continue since it ends before the start of the CDT slot. At 480 [μs], however, a new message is being generated which is not allowed to be forwarded during the Guard Band. This message will thus experience a delay and be forwarded at the next opening of the BE traffic gate.
The implementation can therefore be concluded to be valid and according the specification of the IEEE802.1Qbv standard.

Fixed Guard Band

Two distinct configurations implementing the Fixed Guard Band can be seen from Figure 6.4 and 6.5
From both figures can be seen that the percentage of utilization is equal, unlike the amount and size of messages present. This result adheres to the expectation presented in Chapter 5. One may thus conclude that, depending on the data stream types present, the Fixed Guard Band reserves bandwidth for a constant time duration assuring CDT to be forwarded at its activation time.
Both figures indicate the percentage of utilization by the Fixed Guard Band to be approximately 4.8 [%], leaving an opportunity to forward lower priority data.

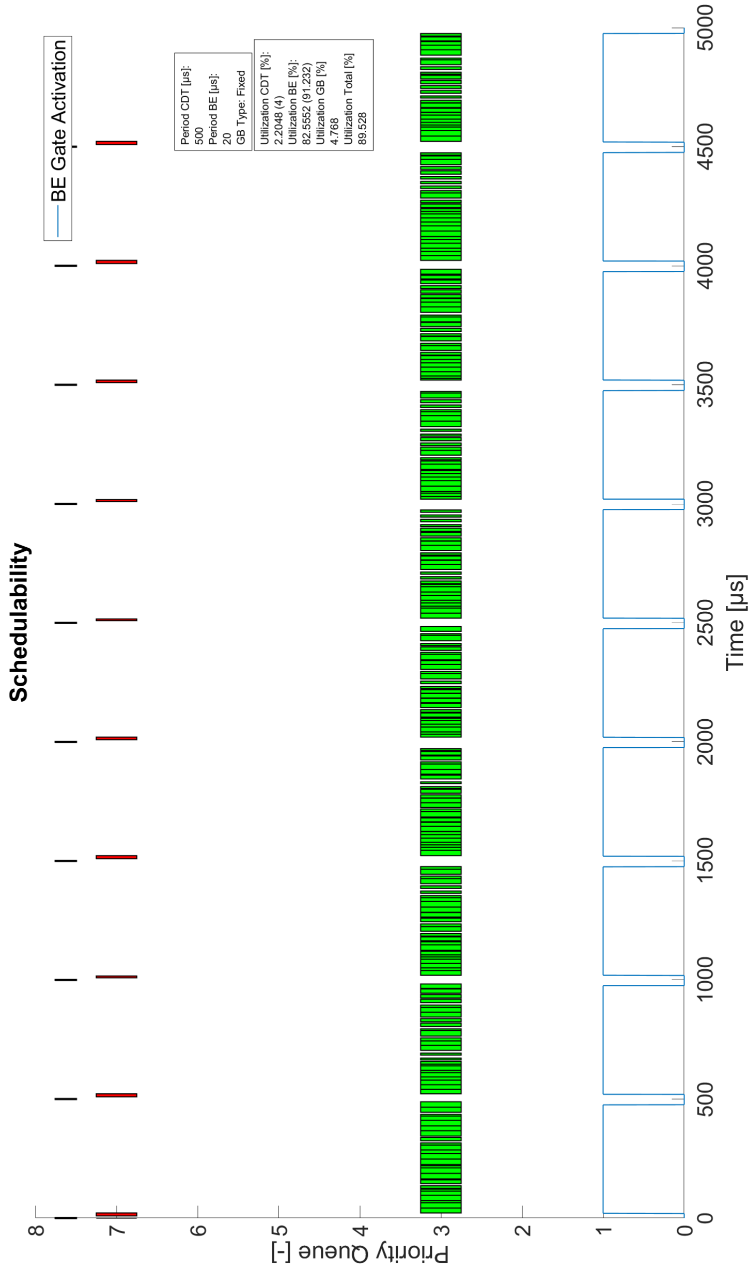

Figure 6.4: Fixed GB, BE Period 20 [μs]

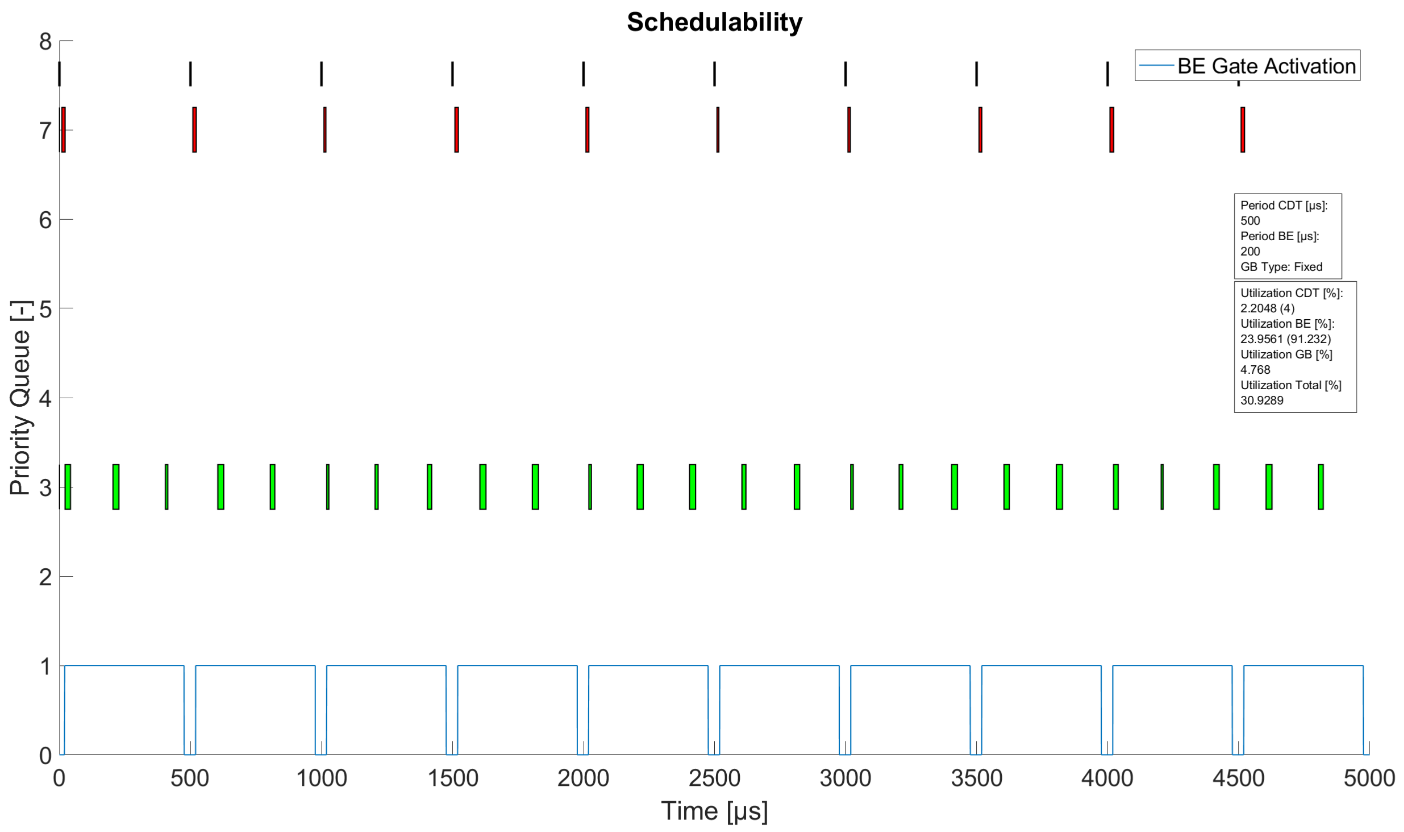

Figure 6.5: Fixed GB, BE Period 200 [μs]

Variable Guard Band

The IEEE802.1Qbv standard implies to operate with a variable starting time of the Guard Band, depending on the maximum payload present within the task set known at compile time.
From Figure 6.6, the expectations presented in Chapter 5 can be confirmed. The configuration of Figure 6.6 has been chosen equal to the one of Figure 6.4, demonstrating the Fixed Guard Band, in which the approach of the Guard Band is the only difference. One may notice that the actuation times of the gates are equal in both approaches, supported by the percentage of utilization.
The duration of bandwidth reservation once the maximum payload is allowed, using the approach of the Variable Guard Band, behaves thus equal to that of the Fixed Guard Band, being only an advantage if the payload size has decreased.

In order to demonstrate the advantage of the Variable Guard Band, by decreasing the maximum allowed payload size for BE traffic, Figure 6.7 presents a significant decrease in the utilization percentage caused by the Guard Band.
The configuration within this figure is set to a maximum payload size of 150 [bytes], arbitrarily chosen, with equal settings for CDT as well as message generation periods.
Analysing both implementations of the Variable Guard Band, Figure 6.6 and 6.7, a noteworthy difference can be observed from the percentage in utilization of the Guard Band, evident by the late termination of the BE gate signal in Figure 6.7. A decrease of approximately 1.7 [%] has been reached by composing a Guard Band being dependent upon the maximum payload size of the BE traffic, in which lower priority data can be forwarded.

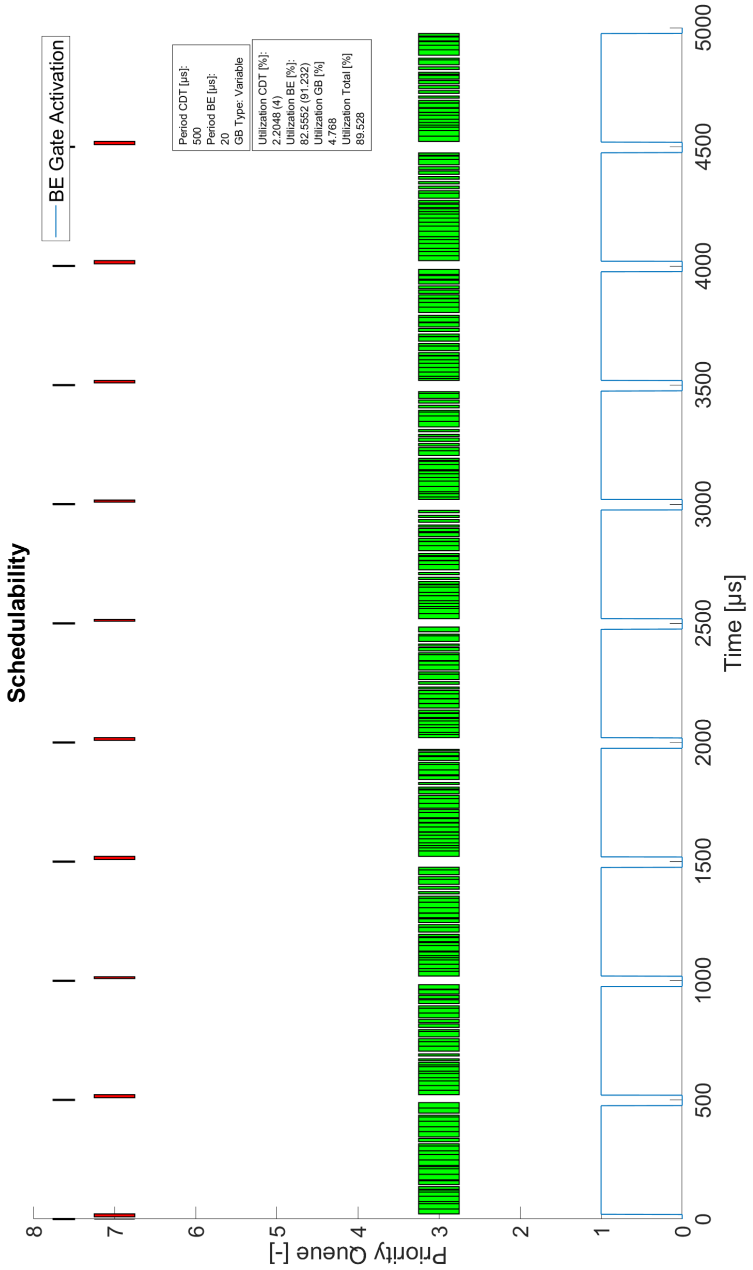

Figure 6.6: Variable GB, BE Period: 20 [μs]; Size: Maximum [bytes]

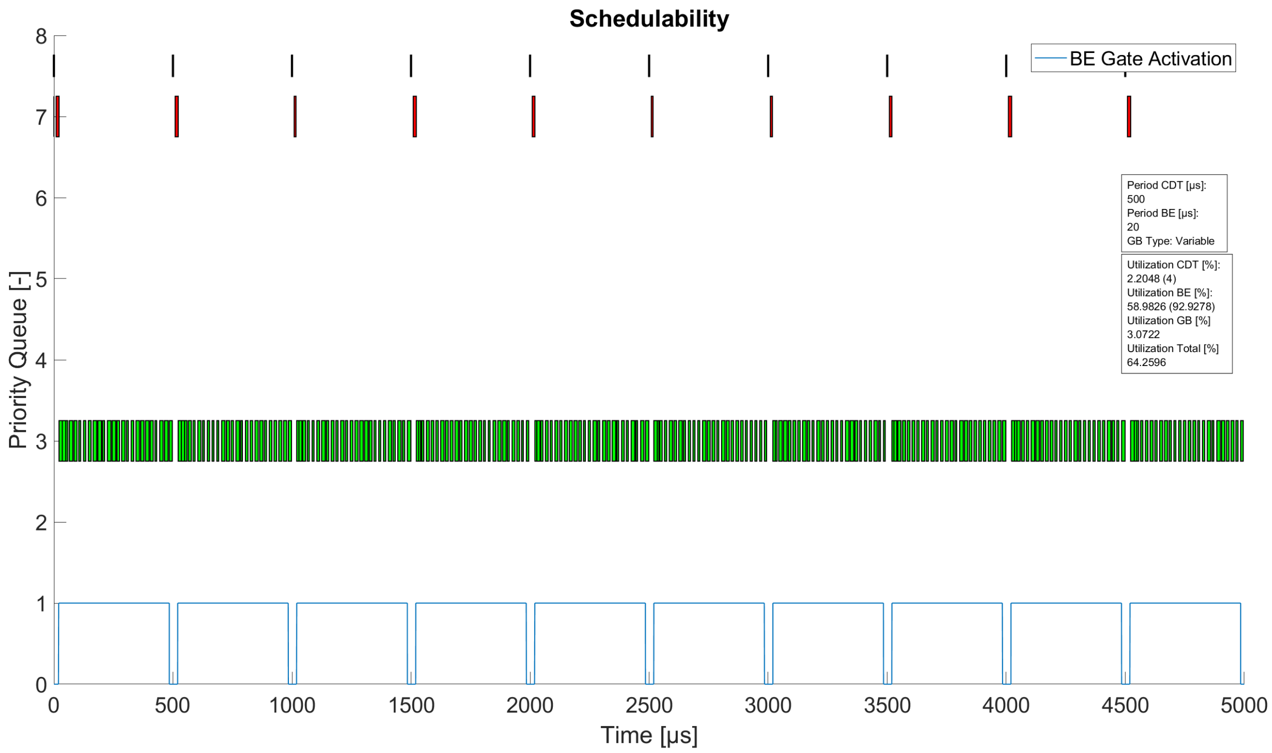

Figure 6.7: Variable GB, BE Period: 20 [μs]; Size: 150 [bytes]

To point out the contrast of the Variable Guard Band Figure 6.8 has been formed, presenting the variation in closure times of the BE gate caused by the payload size.

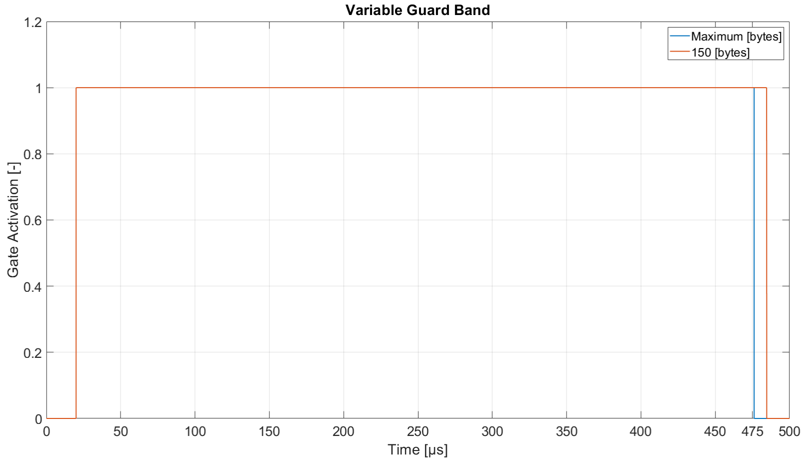

Figure 6.8: Contrast BE gate different payload size

The gate activation line in blue, present in Figure 6.8, indicates the closure of the BE gate, start of the Guard Band, for a maximum sized payload message. This is thus equal to the behaviour of the Fixed Guard Band, being approximately 24 [μs] for BE traffic.

Figure 6.9 indicates the relation of the payload size to the reserved duration of the Variable Guard Band, for which Equation 6.1 holds in the range of, 84 - 298 [bytes], BE message frames for 100 [Mbps] Automotive Ethernet:

$$Time(messageSize) = \frac{messageSize}{12.5} \; [\mu s] \tag{6.1}$$

One may observe that Equation 6.1 has been used before to calculate the forwarding duration over the physical layer to its next location, as presented in Chapter 5 *Switching Fabric & Priority Filtering*. This is done to assure the bus to be available at the time of forwarding CDT.

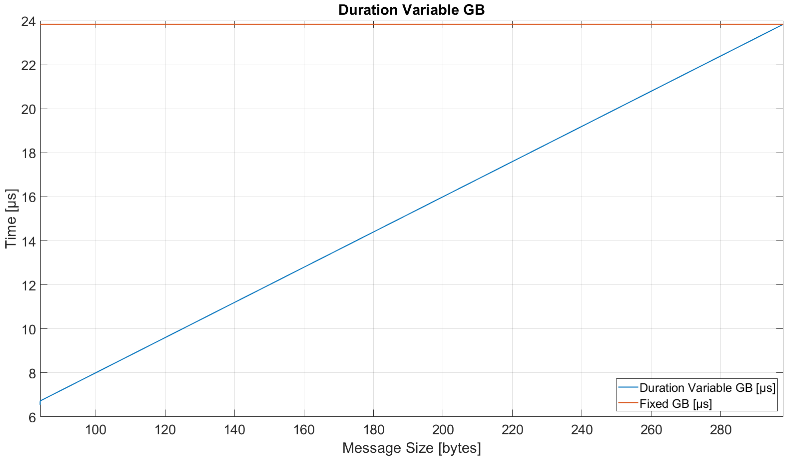

Figure 6.9: Duration Variable Guard Band based on message size

Dynamic Guard Band

As in some configurations the Variable Guard Band may behave equal to the Fixed Guard Band and bandwidth being reserved, which might be enough for a modest pending message frame to be forwarded, an alternative has been proposed, called the Dynamic Guard Band.

While forwarding maximum payload size messages the Guard Band in the Fixed approach would consume approximately 4.8 [%]. Implementing the Dynamic Guard Band decreases this percentage by more than 0.1 [%], as can be seen from Figure 6.10, which is already an advantage over the Variable Guard Band while assuring CDT to be forwarded at activation time.

As the Dynamic Guard Band is based on the Variable Guard Band any decrease in payload size will diminish the bandwidth reserved to serve as a Guard Band. Comparing the results of equal configurations of both approaches does not present any difference, as presented in Figure 6.11 and 6.7.
A minor difference is observed while comparing the Dynamic Guard Band to the approach of the Fixed Guard Band, Figure 6.6 and 6.4, increasing the amount of BE traffic sent by approximately 0.25 [%].

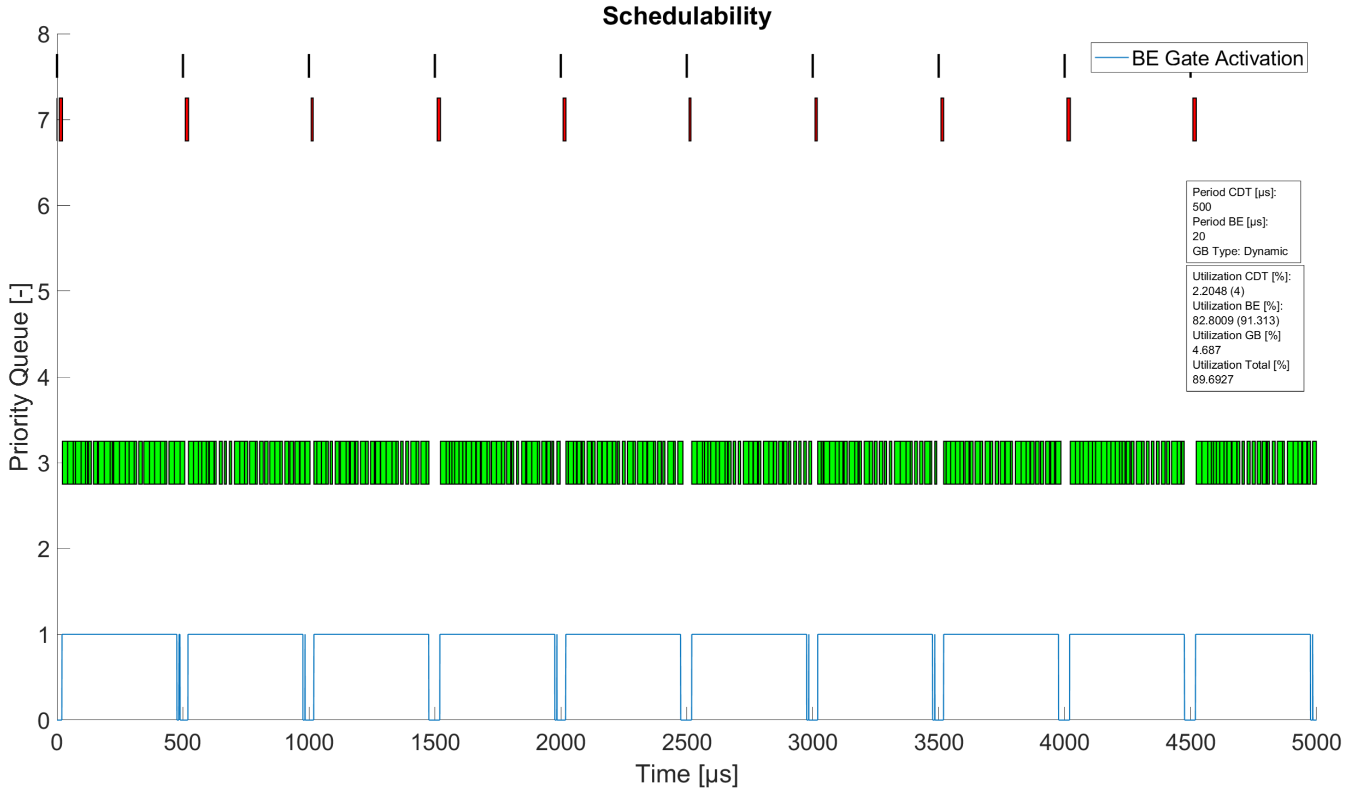

Figure 6.10: Dynamic GB, BE Period: 20 [μs]; Size: Maximum [bytes]

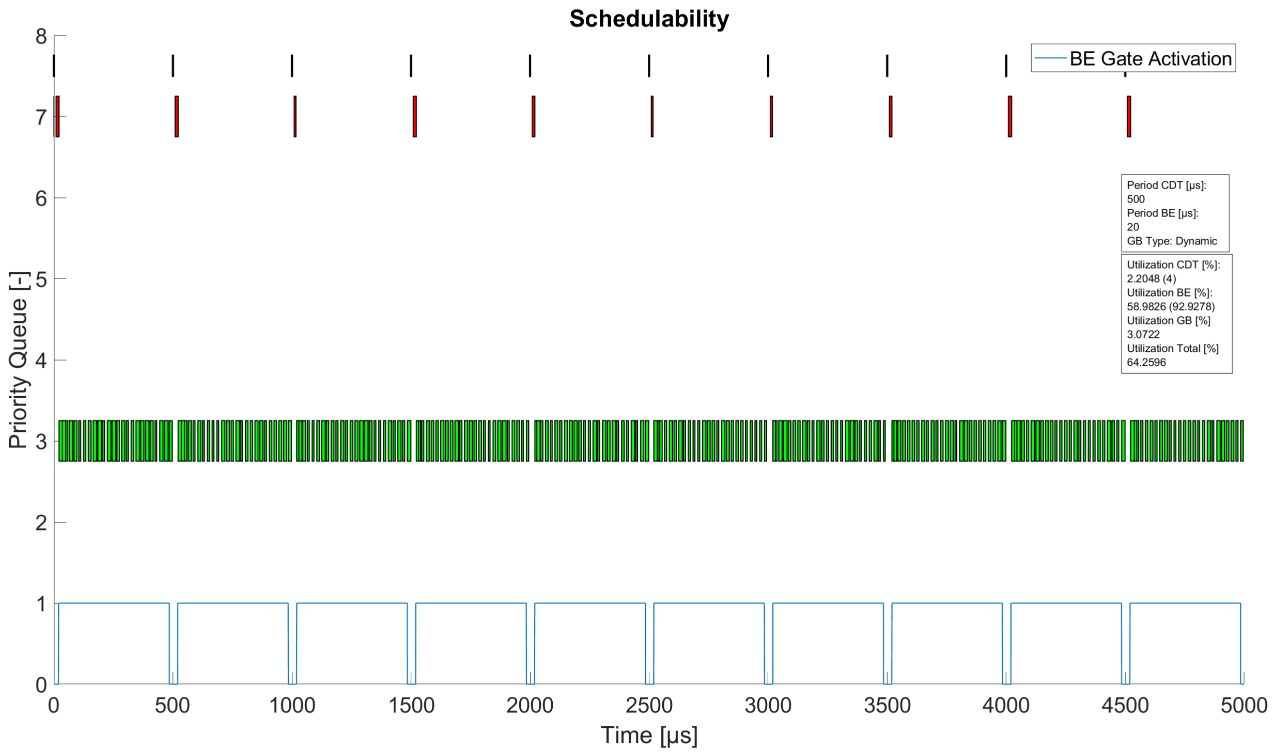

Figure 6.11: Dynamic GB, BE Period: 20 [μs]; Size: 150 [bytes]

The cause of the only constrained influence can be found from the duration of the BE traffic slot and its forwarding sequence, this is being illustrated in Figure 6.12 and 6.13.

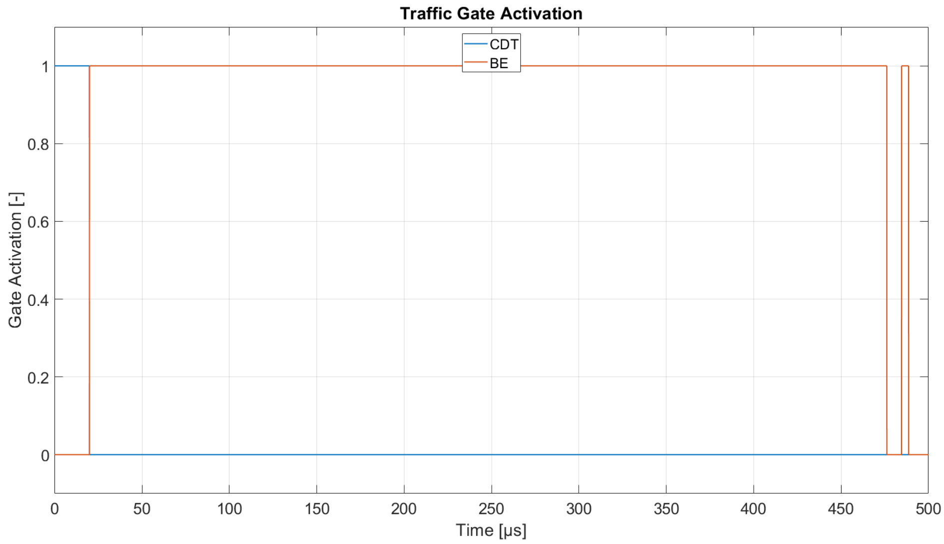

Figure 6.12: Dynamic Guard Band, Gate Activation

The configuration settings for this task set have been set to:

- Simulation time: 500 [μs]
- BE Generation Period: 20 [μs]
- BE Maximum Payload size: 256 [bytes]

From the actuation of the BE gate in Figure 6.12, orange signal, it can be seen that the configuration under investigation identifies as a successful case of the Dynamic Guard Band, forwarding after the time of the statically determined start of the Guard Band. This is also, but less, visible from the gate signal in Figure 6.13 at the bottom.

The gate signal, presented in Figure 6.12, thus presents forwarding during the Guard Band period opposite to the definition in Figure 4.1, still assuring activation of the CDT slot at the intended time.

Figure 6.13 presents four types of information, namely; the generation period of messages in blue, the time at which the message is ready to be forwarded from the egress port in red, the arrival time of the message at the next node in yellow, and finally the control of the BE traffic gate at the bottom in purple.

At the left of Figure 6.13, at time 0 [μs], it can be seen that a message is being generated. Since at this time the BE traffic gate is closed the message is pending in the buffer to be forwarded at the time of opening of the gate. Exactly at 24.6 [μs][1] the initial generated message is being forwarded after which it is received by the next node at approximately 40 [μs]. In the mean while, a newly generated message is present in the buffer due to the generation period chosen. As the BE traffic gate is still open the sequence repeats itself, without the preemption of the higher priority CDT.

If one calculates the number of messages being generated during the simulation period and subsequently inspects the number of messages being forwarded one will find that at the starting time

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[1] Explained in Appendix A.2

of the Guard Band the BE buffer is empty. For this reason, the Guard Band starts at 476.16 [μs], not gaining an advantage over the Fixed Guard Band or Variable Guard Band with a maximum allowable payload size.
At 480 [μs] a message is being generated. Having a specific size, such that it will be forwarded on the communication bus before the start of the next CDT slot. The BE traffic gate is therefore opened and the pending message may continue to be transmitted.

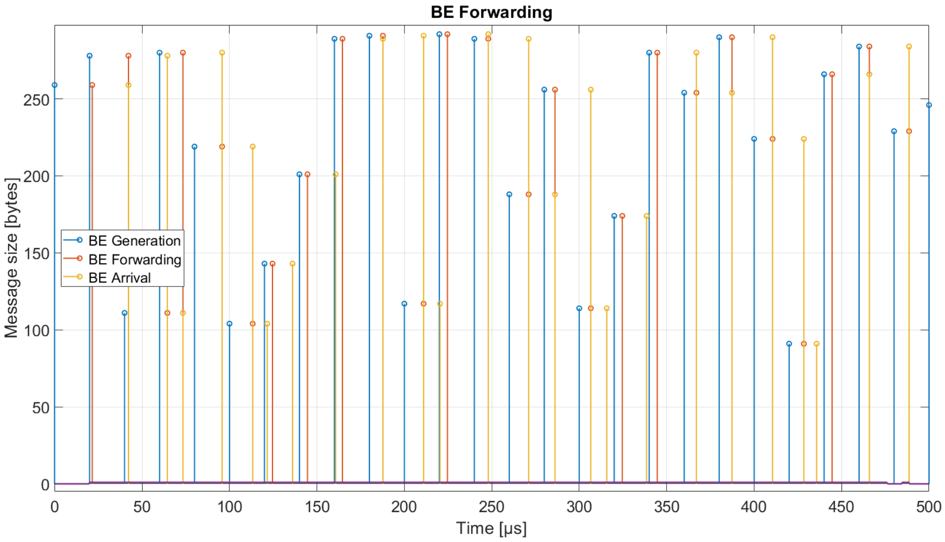

Figure 6.13: Dynamic Guard Band, Forwarding information

In conclusion, to relate back to the expectations stated for the Dynamic Guard Band in Chapter 5, the BE traffic buffer is even empty at high frequent message generation, only forwarding a single message being generated during the active Guard Band.
This same effect is noticeable from BE generation with higher periodic values, as can be seen from Figure 6.14.
Within this configuration, approximately at 4000 [μs], a message is being forwarded since it is being generated during the active Guard Band, being not a pending message in the buffer.

As the lower value of the BE-traffic generation period has been chosen arbitrarily, the simulation has been repeated. This is done to assess the percentage of bandwidth utilization at even higher generation periods, ranging from 5-20 [μs] with an increment of 5 [μs].

Analyzing the results of the parameter sweep indicates that the only schedulable task set, in CDT terms, is the configuration presented in Figure 6.15.
Examining the percentage of utilization of the BE-traffic slots, as well as the overall utilization, demonstrates the excessive availability of data on the communication bus. As the task-set is still schedulable it does delay the timely forwarding of scheduled traffic. This becomes evident once the forwarding at time 2000 [μs] is enlarged, as indicated in Figure 6.16.

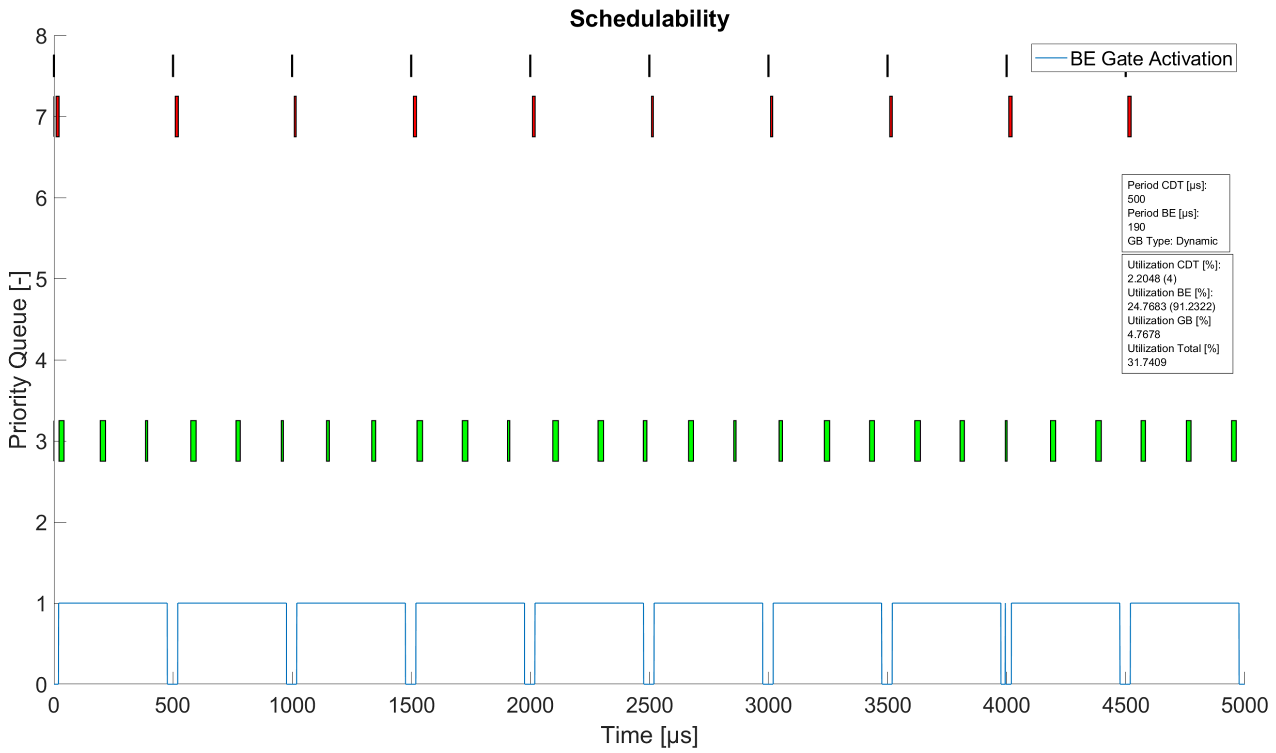

Figure 6.14: Dynamic GB, BE Period: 190 [μs]; Size: Maximum [bytes]

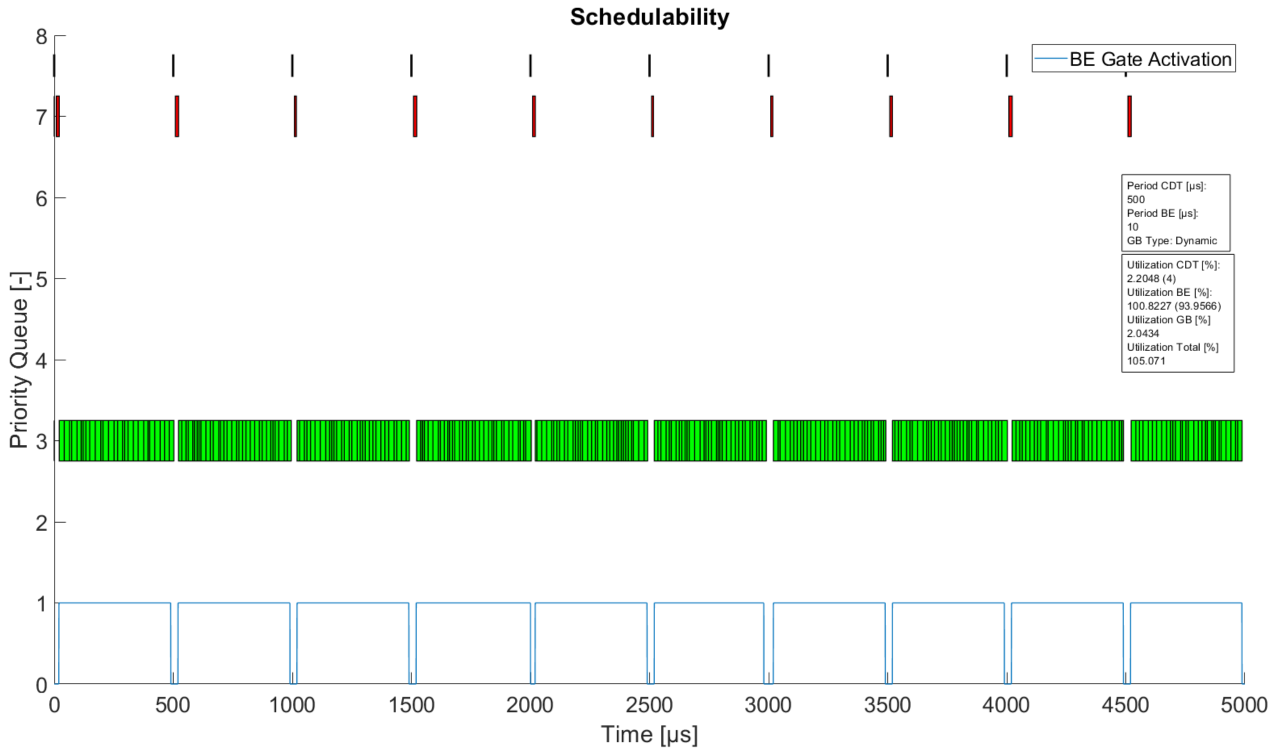

Figure 6.15: Dynamic GB, BE Period: 10 [μs]; Size: Maximum [bytes]

Figure 6.16 presents a frame of BE-traffic being forwarded during the Guard Band period. It however exceeds the activation time of scheduled traffic, delaying transmission of the generated CDT-traffic. Since the CDT-traffic completes transmission before the start of BE-slot it is marked to be schedulable, being still not favorable in terms of low latency forwarding.

Unlike this being the only configuration partly schedulable, it is advised to not be used. The addition of disturbance of which the configuration might be subject to, being scheduled within an IVN, could cause the system to become unschedulable. Moreover, forwarding of data which exceeds the start of the upcoming CDT slot is not allowed, causing this configuration to be insufficient.

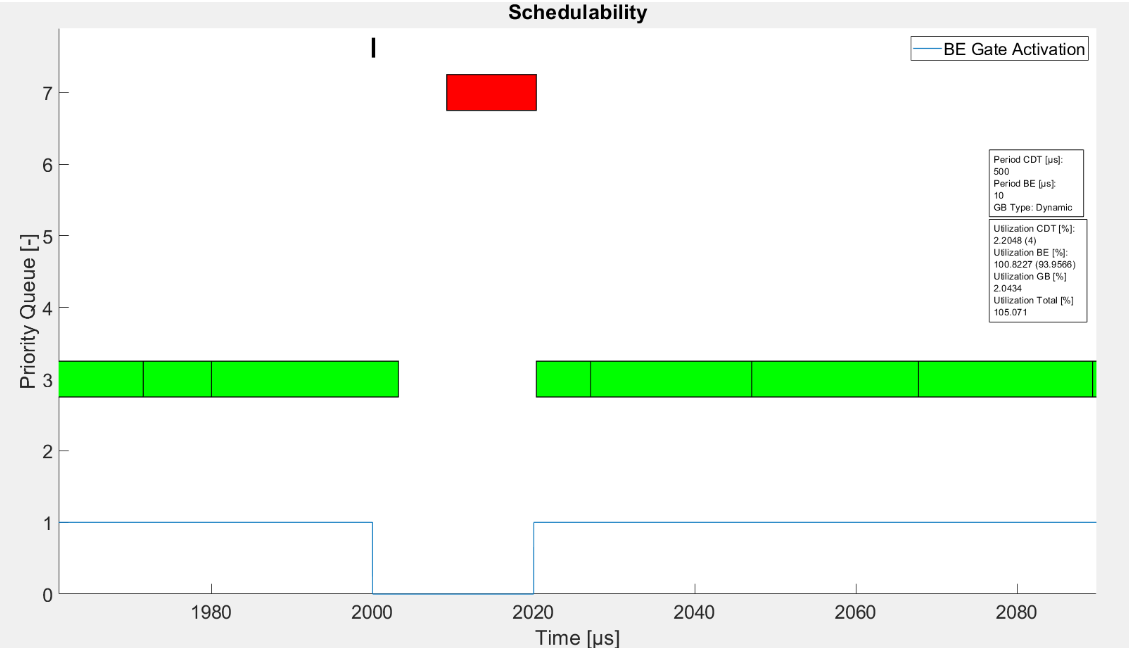

Figure 6.16: Dynamic Guard Band, marginally stable

6.3 Discussion

The results of the simulation indicate the correct performance and construction of the software model, operating as is intended in the IEEE802.1Qbv standard, presented in Chapter 4.
These findings not only provide the ability to verify the schedulability of a configuration, but also demonstrate the justification of the requirements stated in Table 2.1.

Where the influence and composition of the task set regarding the Guard Band have been examined in depth, for both recommendations within the IEEE802.1Qbv standard and the proposed Dynamic Guard Band, one may conclude that the latter is an encouraging approach gaining as much bandwidth utilization per configuration possible.

To summarize the results, the schedulability of a task set can be guaranteed while adhering to the requirements stated in Table 2.1. To which may be added that the generation period of BE-traffic must always be larger than 20 [μs], in order to gain schedulability.
Furthermore, a conclusion can be drawn on the duration of bandwidth being reserved for BE traffic, as can be seen from Table 6.1 categorized per approach used:

Type	Payload Size	Duration	Percentage
Fixed	All sizes	23.84 [μs]	4.768 [%]
Variable	42-256 [bytes]	6.72-23.84 [μs]	1.344-4.768 [%]
Dynamic	42-256 [bytes]	6.72-Dynamic [μs]	1.344-Dynamic [%]

Table 6.1: Duration Bandwidth Reservation per GB

As the transmission rate is provided and the schedulability according to the requirements is guaranteed, the objective of Automotive Ethernet TSN with the Time-Aware Shaper, to be used as an alternative for currently existing communication busses for near future autonomous driving, can be concluded to be an appropriate solution. Given that the configurations are setup equal to the ones presented in the section Results.

It is beyond the scope of this study to examine the influence of AVB traffic on the schedulability of the task set as well as the Guard Band. Further studies, based on the TAS, should take into account scheduling of the multimedia streams as well as the additional BE traffic queues available.

As the behaviour of the switch, being resembled by the simulation model, within this thesis is expected to behave without the addition of any jitter, verification of the software model on a hardware setup might be subject to a variation in the schedulability results. Further research is needed to establish whether the jitter influences the schedulability in a way that the currently configurable task sets become non-schedulable.

Chapter 7

Conclusion

The research performed aimed to assess the implementation of the TSN standard on Automotive Ethernet. This has been done by examining the current application state and presenting its deficiencies, by means of a gap analysis.

From examining the current state of Automotive Ethernet along with the TSN standard for future implementation, could be concluded that information is available to a limited extend.
An important sub-standard, enabling forwarding of scheduled traffic with real-time guarantees, IEEE802.1Qbv, became the subject of the thesis. Narrowing the scope to study the schedulability and influence of the Guard Band, has proven the absence of hardware or software for evaluation purposes.

To examine the configurations possible and the influence of parameter changes on the overall bandwidth utilization, it was decided to develop a simulation model. By means of the simulation model, the user is able to visualize the configuration and assess the influence of different approaches of the Guard Band. Schedulability and advantages over the currently advised Guard Band became evident within the thesis, leaving future research to verify the configurations on devoted TSN hardware.
The TAS standard presented to be a suitable alternative for the currently available communication busses, gaining real-time guarantees while scheduling for safety criticl functions.

The results of this study moreover present that the TSN, and more specifically the TAS standard, is only available in an informative way stating the objectives of the standard rather than the method of implementation. This is also expected to be the reason for the hardware and software being not available, leaving implementation of the standard to be interpreted by the user.

Therefore, Automotive Ethernet utilizing the Time-Aware Shaper standard is proven to be an advantage over currently used communication busses, remaining cautious about the duration before this can be found in production vehicles.

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Appendix A

Supportive Information

A.1 Generation Period CDT

Within the year 2020 Volvo Cars is limiting the maximum speed of their vehicles to 180 [km/h], to diminish the number of casualties caused within traffic [10].
As vehicles tend to become smarter with the ultimate intention to drive autonomously, systems within ADAS need to forward data at a rate in which the requirements of these systems can be met. Assuming to fulfill these requirements with an accuracy of 1 [cm] while driving at the constrained velocity set by Volvo, the sample rate of ADAS components is calculated to be:

$$Vehicle\ speed = \frac{180\ [\frac{km}{h}]}{\frac{3600\ [sec]}{1000\ [m]}} = 50\ [\frac{m}{s}] = 5000\ [\frac{cm}{s}] \tag{A.1}$$

With a 1 [cm] accuracy, 5000 [cm/s] is the sample rate:

$$Sample\ period = \frac{1}{frequency} = \frac{1}{5000\ [Hz]} = 0.0002\ [sec] = 200\ [\mu s] \tag{A.2}$$

The process of sensing, computation and actuation must therefore be performed every 200 [μs].

A.2 Forwarding first BE message

Forwarding of each BE traffic message generated at the start of the simulation time is delayed by the slot size of the CDT.
In addition, each generated message frame, either BE or CDT, experiences a delay of 4.6 [μs] resembling the transmission time through the switch [5].
As in this case the slot size of CDT is set to 20 [μs], the arrival time of the first BE traffic message generated at the egress port is 24.6 [μs].

Using Equation A.3, the forwarding time of the first BE can be calculated:

$$forwardingTime(numberOfSwitches) = (20 * numberOfSwitches) + 4.6\ [\mu s] \tag{A.3}$$

- *numberOfSwitches:* Each additional switch results in an increase of 20 [μs], as the requirements state in Table 2.1