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FLEXIBLE WINDOW-BASED SCHEDULING WITH CRITICAL WORST CASE LATENCY EVALUATIONS FOR REAL TIME TRAFFIC IN TIME SENSITIVE NETWORKS

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By

SHALGHUM KHALED MUFTAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To my father who supported me during all my life and did everything for me to be a successful man in this life.

To my greatly beloved mother, for her continuous prayer, advice, smile, and take care of me.

To my wife for her encouragement to obtain this achievement.

To my sons and daughters as they are the reason that keeps me strong.

To my brother and sisters for their unlimited support and continuous advice during the research journey.

To all my teachers who taught me during all my studying years.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Prof. Ir. Ts. Nor Kamariah Binti Noordin, PhD
Faculty : Engineering

Deterministic and low latency communications are increasingly becoming essential requirements for several safety-critical applications, such as automotive and automation industries. Time-sensitive networking (TSN) is a new Ethernet-based framework introduced to support these applications. TSN differentiates mixed-criticality traffic into three different categories: time-triggered (TT), Audio/Video Bridging (AVB), and best effort (BE). The TT flows are scheduled using a predefined gate control list (GCL) in each selected node targeting deterministic and low latency, extremely low jitter, and no congestion loss. The unscheduled traffic (AVB and BE) share the remainder bandwidth using the credit-based shaper (CBS), with a deterministic latency requirement for AVB but less than TT traffic and no QoS requirements for BE.

Implementing a suitable predefined schedule in all selected nodes is a complex and vital problem. The main challenge is how to guarantee TT requirements without missing AVB deadlines. First, complete isolation between TT windows leads to wasting bandwidth and missing QoS requirements for AVB traffic. Moreover, non-optimized window offsets will degrade the end-to-end latency performance for the associated TT queues, leading to less bandwidth availability for unscheduled transmissions. Also, implementing all GCLs in the selected path based on TT evaluations without considering their impacts on the AVB performance results in improper scheduling designs. Accordingly, three related phases are introduced in this thesis to cover these points as follows.

The first part introduces a flexible window-overlapping scheduling (FWOS) algorithm that allows the TT windows to overlap in GCL implementations. An analytical model for the worst-case end-to-end delay (WCD) is derived for TT traffic using the network calculus (NC) approach and evaluated using a vehicular use case, considering the

overlapping among TT windows by three different metrics: the priority of overlapping, the position of overlapping, and the overlapping ratio (OR). For each given latency deadline, the FWOS algorithm determines the maximum allowable OR that obtains the highest unscheduled bandwidth without missing the TT latency deadlines. Even under a non-overlapping scenario, FWOS obtains less pessimistic latency bounds than the latest related works.

The second part proposes an optimized flexible window-overlapping scheduling (OFWOS) algorithm that optimizes the offset difference (OD) between the same-priority TT windows in the adjacent nodes. Using OD-based GCL implementations, the WCD bound for TT traffic is formulated using NC for a targeted priority queue and assessed with OD under non-overlapping and overlapping-based scenarios. OFWOS obtains more WCD reductions than the previous related works, leading to more flexible overlapping between TT windows in each node. A new scheduling constraint is implemented to control the overlapping, targeting more relaxed GCL implementations with guaranteed TT latency deadlines.

In the third part, the worst-case AVB latency under overlapping-based TT windows (AVB-OBTTW) algorithm is presented to examine the OFWOS effects on AVB-X latency performance, where X represents an AVB queue, i.e., $X \in \{A, B\}$. Separate analytical models are derived using NC to calculate WCD for AVB-X with preemption and non-preemption modes. Both models are evaluated under back-to-back and porosity configurations with light and heavy load conditions. Compared to the latest related works, AVB-OBTTW reduces WCD for AVB-X flows by different percentages depending on OR values. The lowest WCD bound is obtained with the maximum allowable OR that meets TT latency deadlines using the OFWOS algorithm. Thus, combining OFWOS and AVB-OBTTW evaluations can be a helpful guide for TSN designers to implement tighter and more trusted GCL schedules.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENJADUALAN BERASASKAN TETINGKAP YANG FLEKSIBEL DENGAN PENILAIAN LATENSI KES TERBURUK YANG KRITIKAL UNTUK TRAFIK MASA NYATA DALAM RANGKAIAN YANG PEKA MASA

Oleh

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Komunikasi berdeterministik dan berlatensi rendah menjadi keperluan penting untuk beberapa aplikasi kritikal keselamatan, seperti industri automotif dan automasi. Rangkaian peka masa atau time-sensitive networking (TSN) merupakan kerangka kerja baru berasaskan Ethernet yang diperkenalkan untuk menyokong aplikasi-aplikasi ini. Seperti yang diketahui, kes ini menjana pelbagai jenis trafik bergantung kepada keperluan QoS. Oleh itu, TSN membezakan trafik kritikal bercampur kepada tiga kategori yang berbeza: pencetus masa atau time-triggered (TT), penghubung Audio/Video atau Audio/Video Bridging (AVB), dan usaha terbaik atau best effort (BE). Aliran TT dijadualkan menggunakan senarai kawalan gerbang yang telah ditetapkan (GCL) dalam setiap nod menyasarkan deterministik dan latensi rendah, gegaran yang sangat rendah, dan tiada kerugian kesesakan. Trafik tidak berjadual (AVB dan BE) berkongsi baki lebar jalur menggunakan pembentuk berasaskan kredit atau credit-based shaper (CBS), dengan keperluan latensi berdeterministik untuk AVB tetapi kurang daripada trafik TT dan tiada keperluan QoS untuk BE.

Melaksanakan jadual pratakrif yang sesuai dalam semua nod yang dipilih adalah masalah yang rumit dan utama. Cabaran utama ialah bagaimana untuk menjamin keperluan TT tanpa kehilangan tarikh akhir AVB. Pertama, pengasingan lengkap antara tetingkap TT membawa kepada pembaziran lebar jalur dan kehilangan keperluan QoS untuk trafik AVB. Selain itu, ofset tetingkap yang tidak dioptimumkan akan merendahkan prestasi kependaman hujung ke hujung untuk baris gilir TT yang berkaitan, yang membawa kepada ketersediaan jalur lebar yang kurang untuk penghantaran tidak berjadual. Selain itu, adalah penting dan kritikal untuk menilai prestasi AVB di bawah kesan TT untuk melaksanakan GCL yang sesuai bagi setiap kes penggunaan yang disasarkan. Sehubungan itu, tiga fasa berkaitan diperkenalkan dalam tesis ini untuk merangkumi perkara-perkara berikut.

Bahagian pertama memperkenalkan algoritma penjadualan bertindih tetingkap (FWOS) fleksibel yang membolehkan tetingkap TT bertindih dalam pelaksanaan GCL. Model analitik untuk kes terburuk bagi kelewatan hujung ke hujung (WCD) diperoleh untuk trafik TT menggunakan pendekatan kalkulus rangkaian (NC) dan dinilai menggunakan kes penggunaan kenderaan, dengan mengambil kira pertindihan antara tingkap TT dengan tiga metrik berbeza: keutamaan pertindihan, kedudukan pertindihan, dan nisbah pertindihan (OR). Untuk setiap tarikh akhir kependaman yang diberikan, algoritma FWOS menentukan maksimum dibenarkan OR yang memperoleh lebar jalur tidak berjadual tertinggi tanpa kehilangan tarikh akhir kependaman TT. Walaupun di bawah senario yang tidak bertindih, FWOS memperoleh had latensi yang kurang pesimistik daripada kerja-kerja berkaitan yang terkini.

Dalam bahagian kedua, algoritma penjadualan tindih tetingkap fleksibel yang dioptimumkan (OFWOS) dicadangkan untuk mengoptimumkan perbezaan ofset (OD) antara tetingkap TT keutamaan yang sama dalam nod bersebelahan. Menggunakan ODberasas pelaksanaan GCL, WCD ikatan untuk trafik TT dinyatakan menggunakan NC untuk aturan utama yang disasarkan, dan dinilai dengan OD di bawah senario tidak bertindih dan berasaskan pertindihan. OFWOS memperoleh lebih banyak pengurangan WCD daripada kerja berkaitan sebelumnya, yang membawa kepada pertindihan yang lebih fleksibel antara tetingkap TT dalam setiap nod. Kekangan penjadualan baharu dilaksanakan untuk mengawal sasaran bertindih pelaksanaan GCL yang lebih santai tanpa terlepas tarikh akhir latensi TT.

Dalam bahagian ketiga, latensi AVB kes terburuk di bawah algoritma tetingkap TT berasaskan pertindihan (AVB-OBTTW) dibentangkan untuk memeriksa kesan OFWOS pada prestasi kerelatifan AVB-X , di mana X mewakili baris gilir AVB, iaitu, $X \in \{A , B\}$. Model analisis berasingan diperolehi menggunakan NC untuk mengira WCD untuk AVB-X dengan mod pendahuluan dan bukan pendahuluan. Kedua-dua model dinilai di bawah konfigurasi bolak-balik dan porositi dengan keadaan beban ringan dan berat. Berbanding dengan kerja-kerja berkaitan terkini, AVB-OBTTW mengurangkan WCD untuk AVB-X aliran dengan peratusan yang berbeza bergantung kepada OR nilai. WCD Ikatan terendah diperoleh dengan kadar maksimum yang dibenarkan OR memenuhi tarikh akhir latensi TT menggunakan algoritma OFWOS. Oleh itu, gabungan penilaian prestasi OFWOS dan AVB-OBTTW boleh dianggap sebagai panduan berguna bagi pereka bentuk TSN untuk melaksanakan jadual GCL yang lebih ketat dan dipercayai.

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LIST OF ABBREVIATIONS

5G	Fifth generation
3GPP	Third generation partnership project
ADAS	Advanced driver assistance systems
AIS-R(L)	Abbreviated injury scale-right (or -left)
ATS	Asynchronous traffic shaper
AVB	Audio/video bridging
AVB-OBTTW	AVB under overlapping-based time-triggered windows
BE	Best effort
BLS	Burst limiting shaper
BW	Bandwidth
CAN	Controller area network
CAN-FD	Controller area network with flexible data rate
CBS	Credit-based shaper
CPU	Central processing unit
CUC	Centralized user configuration
DA-Cam	Dashboard camera
ECU	Electronic control unit
ES	End system
FIFO	First-in-first-out
FN	First node
FRER	Frame replication and elimination for reliability
FWOS	Flexible window-overlapping scheduling
Gbps	Giga bits per second
GB	Guard band
GCL	Gate-control list

GM	Grand master
GRASP	Greedy randomized adaptive search procedure
HU	Head Up display
gPTP	Generalized precision time protocol
IEC	International electrotechnical commission
IEEE	Institute of electrical and electronic engineers
IP	Internet protocol
Java API	Java application programming interface
JRS	Joint routing and scheduling
LCM	Least common multiple
LDW/TSR	Lane departure warning/traffic sign recognition
LIN	Local interconnect network
MOST	Media oriented serial transport
MTU	Maximum transmission unit
MUX	Multiplexer
NC	Network calculus
NFV	Network functions virtualization
NiVi camera	Night vision camera
OD	Offset difference
OFWOS	Optimized flexible window-overlapping scheduling
OH	Overhead
OR	Overlapping ratio
PS	Peristaltic shaper
QoS	Quality of service
RSE	Rear seat entertainment
RTC	Real-time calculus
SAE	Society of automotive engineers

SDN	Software-defined networking
SRP	Stream reservation protocol
ST	Scheduled traffic
SW	Switch
TAS	Time-aware shaper
TDMA	Time division multiple access
TRCBS	Token regulated credit-based shaping
TSN	Time-sensitive network
TSSDN	Time-sensitive software-defined networking
TT	Time-triggered
UBS	Urgency-based scheduler
UNI	User/network interface
USB	Universal serial bus
UST	Unscheduled traffic
V2D	Vehicle-to-device
V2I	Vehicle-to-infrastructure
V2N	Vehicle-to-network
V2P	Vehicle-to-pedestrian
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
WCD	Worst-case delay
WLAN	Wireless local area network

LIST OF SYMBOLS

N	Number of nodes in the end-to-end path.
IN^h	Number of input ports in node h.
N_q^h	Number of TT queues in node h.
C^h	Egressing rate from node h.
$W_m^h,\ T_m^h$	Duration and period of m-th priority window in node h.
Q_m^h, G_m^h	The m-th priority queue and its gate in node h.
$\mathcal{S}^h$	Number of TT flows in node h.
$s_m^h, \mathcal{F}_m^h$	Number of m-th priority flows and the associated frames in node h.
$f_k^{h,max}$	Largest size of the k-th frames in node h.
$f_{k^+}^{h,max}$	Largest size of higher priority frames in node h.
$t_k^{h,o,i}, t_k^{h,c,i}$	Opening and closing times of the k-th priority window at node h in the i-th cycle.
$t_k^{h,B,i}, t_k^{h,E,i}$	Starting and ending times of the k-th contention-free interval at node h in the i-th cycle.
$t_H^{h,B,i}, t_H^{h,E,i}$	Starting and ending times of the targeted contention-free interval after considering higher-priority overlapping at node h in the i-th cycle.
$t_L^{h,B,i}, t_L^{h,E,i}$	Starting and ending times of the targeted contention-free interval after considering lower-priority overlapping at node h in the i-th cycle.
$L_{k,m}^{h,B,i}, L_{k,m}^{h,E,i}$	Length of overlapping interval between the k-th and m-th windows from the opening and closing edges of k-th window, respectively.
$OR_{k,m}^{h,B,i}, OR_{k,m}^{h,E,i}$	Overlapping ratio between the k-th and m-th windows at node h in the i-th cycle from the opening and closing edges of k-th window, respectively.
$OR_{k,H}^{h,B,i}, OR_{k,H}^{h,E,i}$	Highest overlapping ratio between the k-th priority and higher-priority windows at node h in the i-th cycle from the opening and closing edges of the k-th window, respectively.

$OR_{k,L}^{h,B,i}$, $OR_{k,L}^{h,E,i}$	Highest overlapping ratio between the k-th and lower-priority windows at node h in the i-th cycle from the opening and closing edges of k-th window, respectively.
$OR_{H,L}^{o,c}$	Sum of overlapping ratios with the higher-priority windows from the opening-edge and lower-priority windows from the closing-edge.
$R_k^{h,i}$	Relative offset of the i-th contention-free window from the opening-edge.
$R_k^{h,j,i}$	Relative offset of the j-th contention-free window considering the i-th window as benchmark.
T_{GCL}^h	GCL hyper-period
BW_{unsch}^h	Unscheduled bandwidth in node h.
M	Number of contention-free windows in the GCL hyper-period.
$\overline{W}_k^{h,i}$	Length of the k-th contention-free window in the i-th cycle.
WT_k^h	Maximum waiting time for the k-th frame in node h.
$D_{k,select}^{h,max}$	Selection delay of the largest k-th priority frame from node h.
$D_{prop}^{h,h-1}$	Propagation delay between $h-1$ and h.
D_{proc}^h	Processing delay at node h.
$\beta_k^{h,u}(t)$, $\beta_k^{h,l}(t)$	Upper and lower bounds of the service curve for the k-th priority traffic in node h.
$\alpha_k^{h,u}(t)$, $\alpha_k^{h,l}(t)$	Upper and lower bounds of the arrival curve for the k-th priority traffic in node h.
WCD_k^h	Worst-case delay experienced by the k-the frame at node h.
WCD_k^{total}	Worst-case end-to-end delay experienced by the k-the frame.
$e2e_k$	End-to-end latency deadline for the k-th priority traffic.
$OD_k^{h-1,h}$	Offset difference between the k-th priority windows in nodes $h-1$ and h.
$t_{k,in}^{h,i}$	Time when the k-th priority frame reaches the h-input port in the i-th cycle.
$t_{k,queue}^{h,i}$	Time when the k-th priority frame reaches the associated queue at node h in the i-th cycle.

$D^{h}_{k,queue}$	Queuing delay experienced by the k-th priority frame at node h.
$OD^{h-1,h}_{k,opt}$	Optimal offset difference between the k-th priority windows in $h-1$ and h.
$OD^{o}_{H,opt}$, $OD^{c}_{H,opt}$	Optimal offset difference between the same priority windows in the adjacent nodes when the window overlaps with higher-priority windows from the opening and closing edges, respectively.
$OD^{o}_{L,opt}$, $OD^{c}_{L,opt}$	Optimal offset difference between the same priority windows in the adjacent nodes when the window overlaps with lower-priority windows from the opening and closing edges, respectively.
N^{h}_{TT}	Number of TT queues in node h.
$M^{h}_{TT_k}$	Number of k-th open windows in the hyper-period, where k is the window order.
NW^{h}_{GCL}	Number of TT windows in the hyper-period
C^{h}	Egressing rate from node h.
$W^{h}_{TT_k}$, $T^{h}_{TT_k}$	Duration and period of k-th window in node h, where k is the window order in the hyper-period.
$Q^{h}_{TT_k}$	The k-th priority queue and its gate in node h.
τ_{TT_k}	The k-th TT flow.
τ_{X_m}	The m-th AVB-X flow.
$f^{h,max}_{AVB}$	Largest size of AVB frames in node h.
$idSl_X$ & $sdSl_X$	Idle and sending slopes of AVB-X queue.
$cr_X(t)$	Credit of the AVB-X queue.
cr^{min}_X & cr^{max}_X	Minimum and maximum credit bounds of AVB-X queue.
$t^{h,o}_k$, $t^{h,c}_k$	Opening and closing times of the k-th TT window in the hyper-period.
$L^{h}_{k,k+1}$	Length of overlapping interval between k-th and $(k+1)$-th windows at node h.
$OR^{h}_{k,k+1}$	Overlapping ratio between k-th and $(k+1)$-th windows at node h.

$OD_{j,i}^{h}$	Offset difference between the j-th and i-th TT windows at node h.
OH_{j}^{h}	Overhead interval after j-th TT window at node h.
$GAP_{j,j+1}^{h}$	Expected unoccupied gap between j-th and $(j+1)$-th TT windows at node h.
$GB_{j}^{h,p}$ & $GB_{j}^{h,np}$	Length of preemption and non-preemption guard bands for the j-th TT window at node h.
$R_{TT_k}^{h}(t)$	Arrival process of the k-th TT traffic.
$\alpha_{TT_k}^{h}(t)$	Arrival curve of the k-th TT traffic.
$\alpha_{OH}^{h,i}(t)$	Arrival curve during overhead intervals in the i-the cycle.
$\alpha_{G^p+TT}^{h,i}(t)$	Aggregate arrival curve from TT windows and related preemption protection intervals in the i-the cycle.
$\alpha_{G^p+TT+GAP}^{h,i}(t)$	Aggregate arrival curve from TT windows, related preemption protection intervals and expected unoccupied gaps in the i-the cycle.
$\alpha_{G^{np}+TT}^{h,i}(t)$	Aggregate arrival curve from TT windows and related non-preemption protection intervals in the i-the cycle.
$R_{X}^{h}(t)$, $R_{X}^{h*}(t)$	Arrival and departure processes for AVB-X traffic at node h.
Δt_{X}^{+}, Δt_{X}^{-}, Δt_{X}^{0}	Credit increasing, decreasing, and frozen intervals for AVB-X queue.
$\sigma_{X_m}^{h}$ & $\rho_{X_m}^{h}$	Framing size and long-term rate of τ_{X_m} at node h.
$\alpha_{X,sum}^{[h-1,h],p(np)}(t)$	Sum of individual AVB-X arrival curves transferred from $h-1$ to h.
$\alpha_{X,link}^{[h-1,h]}(t)$	Arrival curve of AVB-X traffic with link speed shaper.
$\alpha_{X,CBS}^{[h-1,h],p(np)}(t)$	Arrival curve of AVB-X traffic with CBS constraints.
$f_{X}^{[h-1,h],max}$	Largest AVB-X frame sent from $h-1$ to h.
$\alpha_{X}^{[h-1,h],p(np)}(t)$	Aggregate arrival curve for AVB-X traffic sent from $h-1$ to h.
$D_{X,select}^{h}$	Selection delay of the AVB-X frame from node h.
$D_{prop}^{[h-1,h]}$	Propagation delay between $h-1$ and h.

D_{proc}^{h}	Processing delay at node h.
$D_{X,queue}^{h,p(np)}$	Queuing delay experienced by the AVB-X frame at node h with preemption (p) or non-preemption (np) mode.
$\beta_{X}^{h,p(np)}(t)$	Lower bound service curve for the AVB-X frame at node h with preemption (p) or non-preemption (np) mode.
$\alpha_{X}^{h,p(np)}(t)$	Upper bound arrival curve for the AVB-X frame at node h with preemption (p) or non-preemption (np) mode.
$WCD_{X}^{h,p(np)}$	Worst-case delay experienced by the AVB-X frame at node h with preemption (p) or non-preemption (np) mode.
$WCD_{X}^{p(np)}$	Worst-case end-to-end delay experienced by the AVB-X frame with preemption (p) or non-preemption (np) mode.

CHAPTER 1

INTRODUCTION

This chapter first presents the research significance for real-time communications, followed by the related research problems. Then research objectives are introduced to consider the problems, with a brief methodology explaining how they can be achieved. Finally, this chapter ends with listing research contributions followed by thesis organization.

1.1 Background and motivation

For end-to-end data transmissions, safety-critical real-time applications, e.g., automotive and automation industries, require deterministic and low latency performance. Failing to comply with these requirements may cause dangerous situations for humans or considerable economic waste. Many technologies have been proposed to support these applications. One of which is the Ethernet network, as it has enough bandwidth and feasible cost for real-time scenarios. Although multiple Ethernet-based protocols have been previously introduced, such as Audio/Video Bridging (AVB) Ethernet and time-triggered (TT) Ethernet, they cannot manage safety-critical transmissions and achieve the requirements.

As an extension to TT-Ethernet protocol, the time-sensitive networking (TSN) has been standardized by the IEEE TSN task group to support safety-critical environments. The TSN features include synchronization, network management, access control, and reliability to support TT flows targeting deterministic and low latency, extremely low jitter, and no congestion loss [1]. In the presence of TT traffic, the TSN framework is designed to serve AVB traffic with lower quality-of-service (QoS) requirements and Best Effort (BE) flows with no QoS guarantees. These extensions interested many experts and companies to espouse the TSN technology.

As defined in the IEEE 802.1Qbv standard [2], the TSN framework integrates TT flows using a time-aware shaping (TAS) technique which operates as a time-gating mechanism controlled by the gate control list (GCL) scheduled in each networking node. Thesepredefined schedules (GCLs) control accessing TT flows through the physical links with a global synchronization constraint. For unscheduled traffic (AVB and BE) configurations, the TSN switching applies the credit-based shaping (CBS) technique according to those TT schedules, as defined in IEEE 802.1Qav [3]. Designing appropriate GCLs in all selected nodes while guaranteeing QoS requirements for critical time flows is a complex and vital matter. The designer has to pay the highest attention to two significant aspects; the TT latency requirements and the impact on unscheduled real-time traffic [4].

1.2 Problem statements

As mentioned, TSN standards introduce several protocols to specify synchronization, network management, traffic control, and reliability aspects to support mixed-criticality applications, such as aerospace, automotive, and automation industries. However, other projects targeting some significant amendments are still under research and have not standardized yet, such as IEC/IEEE 60802 TSN Profile for industrial automation and P802.1DG for automotive in-vehicle networks. Thus, the gap is still open between TSN architecture and related applications. One of these ambiguous issues is how to implement an appropriate GCL for each targeted use case. Implementing a suitable GCL timing table for TT traffic in all selected switches while ensuring latency requirements of critical time streams is a complicated and crucial problem. The complexity arises from the difficulties to satisfy TT demands without missing the QoS requirements for AVB traffic. Accordingly, the following related problems are still unconsidered.

- In the TSN standard, the unscheduled traffic (AVB and BE) is prevented to be transmitted if any TT window is open and enough bandwidth must be granted for TT queues to ensure their requirements. All unscheduled flows will share the remaining time intervals when all TT windows are closed. Moreover, in front of each TT window, a guard band is assigned to protect TT transmissions from any incomplete unscheduled transmissions. Thus, complete isolation between TT windows results in considerable bandwidth waste from the guard bands, leading to missing QoS requirements for AVB traffic.

- The offset difference between the same priority windows in the adjacent nodes is very important. Non-optimized window offsets will degrade the end-to-end latency performance for the associated TT queues, leading to more pessimistic worst-case performance. Thus, less overlapping flexibility between TT windows must be applied to meet targeted latency deadlines, resulting in less bandwidth availability for unscheduled transmissions. Although several window-based scheduling algorithms have considered the offset difference between different priority queues at the same node, no one has optimized the offset difference between the same priority windows in the adjacent nodes.

- Implementing all GCLs in the selected path based on TT evaluations without considering their impacts on the AVB performance results in improper scheduling designs. It is essential and critical to evaluate the AVB performance under TT effects to obtain suitable GCL implementations for each targeted use case. All the previous worst-case evaluations for AVB traffic have been addressed based on complete isolation between TT windows. Thus, a comprehensive view of the worst-case AVB performance under TT overlaps is essential to make critical tradeoffs with TT evaluations and implement the most appropriate GCL designs.

1.3 Research objectives

Based on the problems above, the main related objectives of this research are listed as follows:

(i) To propose a flexible scheduling approach that allows TT windows to overlap, aiming to maximize unscheduled bandwidth as much as possible without missing the worst-case latency deadlines for TT traffic.

(ii) To optimize the offset difference between the same priority windows in the adjacent nodes under all overlapping situations between TT windows at the same node, aiming to increase the overlapping flexibility and then improve unscheduled bandwidth.

(iii) To formulate and evaluate the worst-case AVB latency under overlapping-based TT windows, aiming to reduce AVB latency and make critical design optimizations and tradeoffs for appropriate GCL implementations.

1.4 Research scope

This research focuses on vehicular application as one of the real-time scenarios that require more attentions to meet current and future needs. Higher degree of intelligence requires more complicated vehicle architecture and professional communication techniques. Currently, several protocols have been presented to facilitate in-vehicle and vehicle to outside communications. For in-vehicle communications, the controller area network (CAN), local interconnect network (LIN), FlexRay, and media oriented serial transport (MOST) protocols are introduced to serve automotive topology with different features. However, all these techniques with current versions have some related limitations to support higher levels of automation, as discussed in Section 2.1.3. To benefit from its flexibility and scalability, the Audio/Video Bridging Ethernet (AVB-Ethernet) protocol is proposed to serve infotainment application. After that, AVB-Ethernet is developed into the time-sensitive networking (TSN) technology to support safety-critical applications, including autonomous vehicles. Several TSN standards are presented to obtain guaranteed QoS requirements for hard real-time traffic, resulting in enormous TSN-based research proposals on automotive application. Based on that, the TSN protocol is chosen in this research to connect in-vehicle components.

The TSN features include synchronization, network control and management, traffic scheduling and shaping, preemption, and reliability aspects. This thesis is dedicated to studying traffic scheduling and shaping in TSN, considering the preemption and non-preemption techniques between hard real-time traffic (TT flows) and soft real-time traffic (AVB flows). The time-aware shaping (TAS) mechanism is considered under full synchronization guarantee between all TSN elements for traffic shaping. A predefined GCL implementation is proposed under flexible window-overlapping with a comprehensive performance evaluation for TT traffic under all overlapping scenarios, as presented in Chapter 4. The presented scheduling algorithm in Chapter 4 is extended in Chapter 5 to include the offset difference (OD) between the same priority TT windows in the adjacent nodes. Critical OD-based optimizations under non-overlapping and overlapping-based GCL implementations are addressed in Chapter 5. Based on the proposed model in Chapter 5, the AVB performance is studied using credit-based shaping (CBS) in Chapter 6. The preemption techniques defined in the IEEE 802.1Qbu protocol are applied to specify the AVB performance under porosity and back-to-back configurations. For performance evaluations, we examine the worst-case latency and bandwidth for the associated traffic types under all overlapping conditions between TT windows. Accordingly, the scope of this thesis is illustrated in Figure 1.1. All relevant methods and protocols used to achieve this thesis's pertinent objectives are colored in grey, as shown in Figure 1.1. The uncolored boxes represent other protocols or techniques that are not covered in this thesis.

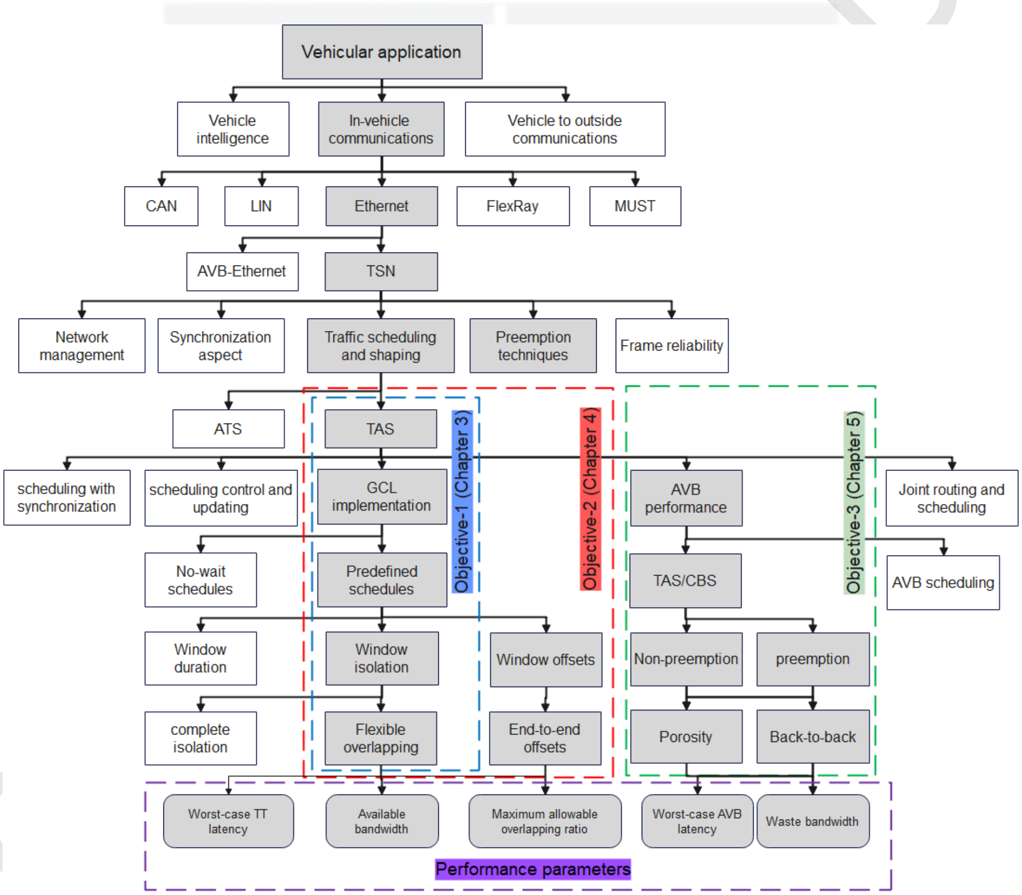

Figure 1.1: Study scope.

1.5 Brief methodology

In order to achieve the aforementioned objectives, the main three phases of this thesis are summarized in Figure 1.2, showing all main inputs and outputs for each proposed algorithm, analytical formulation approach used, use case applied for related performance evaluations, evaluation metrics, and the sequence of the associated steps. As shown in Figure 1.2, the network calculus (NC) approach is used to formulate the worst-case end-to-end latency for TT traffic, in Phases 1 and 2, and AVB traffic in Phase 3. Also, all models are assessed using a vehicular use case considering the latency and bandwidth performances for the associated traffic type, leading to obtain some performance enhancements for soft real-time traffic.

In the first stage, a flexible window-overlapping scheduling (FWOS) algorithm is proposed to improve the solution space for unscheduled critical time traffic by specifying the maximum allowable overlapping ratio (OR) between TT windows with guaranteed TT latency deadlines. First, the initial network and traffic parameters are used to implement GCL schedules in the selected nodes, and then formulate the associated arrival and service curves, which can be used to determine worst-case TT latency. The TT latency form is assessed using a vehicular topology considering all overlapping conditions. After these evaluations, we can determine the maximum allowable OR that obtains the highest unscheduled bandwidth without missing worst-case TT latency deadlines.

In the second stage, an optimized flexible window-overlapping scheduling (OFWOS) algorithm is proposed to optimize the offset difference (OD) between the same priority TT windows in the adjacent nodes. From the beginning, OD is considered as a primary design factor to implement GCL in each selected node with other parameters that are considered in the first phase. Using the same steps in the first stage, the worst-case TT latency is formulated with adjustable OD between adjacent nodes and variable OR at the same node. After evaluating the derived TT latency form under each overlapping condition, the optimal OD can be determined when the latency is the lowest.

In the third stage, the worst-case AVB latency under overlapping-based TT windows (AVB-OBTTW) algorithm is presented to study and evaluate TT impacts on the AVB performance according to the OFWOS algorithm. Using the GCL implementation based on the OFWOS algorithm with AVB traffic parameters, selected preemption mode, and CBS limitations, the worst-case AVB latency is formulated and evaluated using the same use case. Based on the selected preemption mode and the configuration pattern used, the AVB latency is assessed under all overlapping cases, resulting in a complete view for the worst-case AVB latency under TT overlaps. Combining TT and AVB evaluations under the same GCL implementation assists TSN designers to make critical optimizations and tradeoffs that can be used to obtain a suitable GCL for each targeted use case.

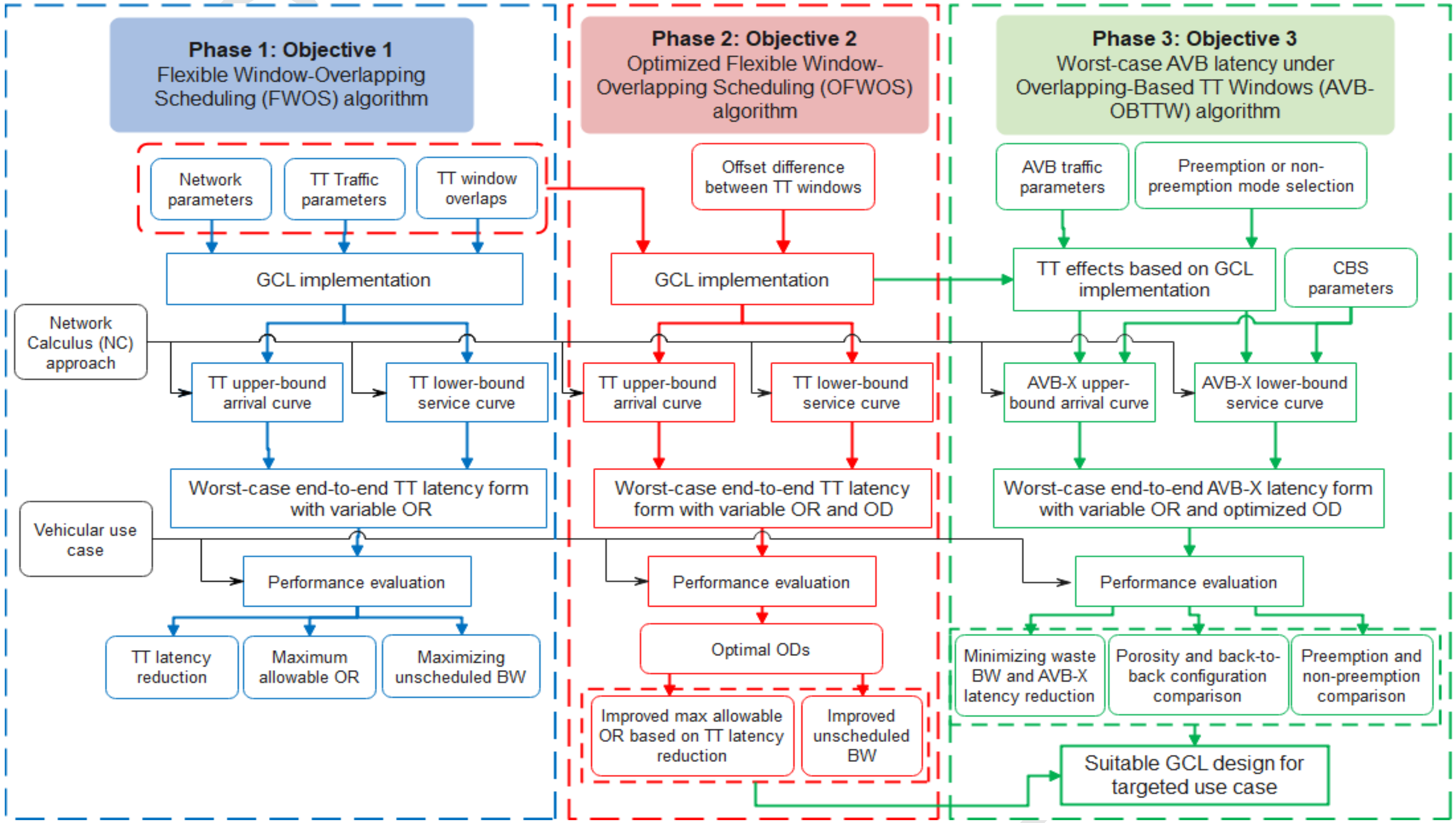

Figure 1.2: Methodology organization.

1.6 Research contributions

The research contributions are summarized in the following three parts:

(i) The FWOS algorithm formulates the worst-case end-to-end delay (WCD) for TT traffic based on flexible overlapping between related transmission windows using the network calculus (NC) approach. The FWOS algorithm is evaluated under a realistic vehicle use case considering three overlapping metrics: the priority of overlapping, the position of overlapping, and the overlapping ratio (OR). A critical discussion is introduced based on GCL design parameters. For each given latency deadline, the FWOS algorithm defines the maximum allowable OR that obtains the best solution space for unscheduled traffic, while guaranteeing TT latency requirements at the same time. Additionally, even under non-overlapping GCL implementation, the FWOS algorithm achieves more WCD reductions compared to the latest related works.

(ii) The OFWOS algorithm optimizes OD between the same priority windows in the adjoining nodes. First, The OFWOS model presents the GCL schedules as mathematical expressions under variable OD between same-priority windows in the adjacent nodes and adjustable OR between different priority windows in each selected node. Then, WCD bounds are formulated using NC and assessed for a targeted TT queue under the whole expected range of OD and OR. Critical OD optimizations are provided and discussed considering all overlapping situations between TT windows. The OFWOS algorithm achieves less pessimistic WCD bounds for TT traffic compared with the previous related works under all overlapping situations, leading to saving more bandwidth for unscheduled streams. Based on the optimal OD and related maximum allowable OR, a new scheduling constraint is formulated to ensure worst-case latency deadlines for TT queues using more relaxed GCL implementations.

(iii) The AVB-OBTTW algorithm presents closed-form expressions for the worst-case AVB-X latency under overlapping-based TT windows, where X represents one of AVB queues (i.e., $X \in \{A, B\}$). First, the GCL schedules are mathematically expressed in each node based on adjustable OR between TT windows in the hyper-period. Then, the upper bound arrival curve and lower bound service curve are determined to calculate WCD bounds for AVB-X traffic using the Network Calculus approach. Separate mathematical models are derived with preemption and non-preemption modes. The AVB-OBTTW algorithm is evaluated under back-to-back and porosity configurations with light and heavy load conditions. Under each evaluation scenario, the preemption and non-preemption impacts on WCD bounds are compared under an adjustable overlapping ratio between TT windows. Compared to the latest related works, AVB-OBTTW reduces WCD bounds for AVB-X flows by different percentages depending on OR values. The lowest WCD bound is obtained with the maximum allowable OR that meets TT latency deadlines using the OFWOS algorithm.

1.7 Thesis organization

The remainder of this thesis is organized as follows:

Chapter 2 presents a brief background about vehicular application with its intelligence requirements and related communications. More details are introduced for in-vehicle communication networks with a summarized comparison. Then, a brief overview of TSN is presented with its main standards that were introduced to support safety-critical applications. More details are presented for TSN amendments in traffic shaping and scheduling. Then, an overall classification for TSN scheduling research studies is illustrated according to the related objectives and contributions. More critical discussions are provided in detail for studies that considered thesis problems drawn in Section 1.2. Finally, a quick review of worst-case latency evaluation approaches in TSN is presented.

Chapter 3 introduces the overall research framework. First, as all thesis contributions are analytical-based solutions formulated using NC, its fundamental background to calculate worst-case latency bounds for real-time applications is introduced. Then, the methodology for each objective is explained in some detail, showing the main difference with the benchmarks that are the closest to the proposed models. After that, validation of benchmarks is presented based on the referred model assumptions. Finally, we specify the vehicular use case with all general assumptions that are used to evaluate the proposed algorithms in Chapter 4-6.

Chapter 4 proposes a flexible window-overlapping scheduling (FWOS) algorithm that allows different priority TT windows to overlap in each selected node. First, the main FWOS assumptions with fundamental formulations are illustrated. Then, the worst-case end-to-end latency analysis for TT traffic is presented using a lower-bound service curve and upper-bound arrival curve. To determine these curves, the duration of contention-free intervals and the maximum waiting time in each selected node are derived for the targeted TT queue. Based on these analytical formulations, the FWOS performance is assessed using a realistic vehicular use case under all overlapping situations. Finally, a critical comparison between FWOS and other related works is provided proving the QoS improvement using FWOS even under non-overlapping scenarios.

Chapter 5 proposes an optimized flexible window-overlapping scheduling (OFWOS) algorithm that optimizes the offset difference (OD) between the same priority windows in the adjoining nodes. First, the initial OFWOS model assumptions are introduced. Then, the GCL schedules are mathematically formulated in all selected nodes on each transmission path assuming variable OD between the same priority windows in the adjacent nodes and adjustable OR between different priority windows at the same node. Based on these formulations, the WCD boundaries for the targeted TT queue are analysed using more tight contention-free and waiting time intervals. After that, the OFWOS algorithm is assessed, leading to an optimal OD for each overlapping condition. A comparison between OFWOS and other related works is provided. Finally, a new scheduling constraint is implemented to bound TT overlaps aiming to maximize the unscheduled bandwidth without missing TT latency deadlines.

Chapter 6 proposes a worst-case AVB latency under overlapping-based TT windows (AVB-OBTTW) algorithm. First, some design decisions for the proposed model are described. The initial stage for the system model is implementing GCL schedules as mathematical relations with assuming flexible overlapping between TT windows. Then, the worst impact of TT arrivals according to the formulated GCL designs is defined for non-overlapped and overlapped windows. The worst TT impact is assumed to formulate a lower-bound AVB service curve, and the upper-bound AVB arrival curve is bounded using the aggregate individual arrival shaper, link speed shaper, and credit-based shaper. After that, the worst-case latency for AVB traffic is determined using these curves. All these formulations are derived with preemption and non-preemption modes separately. To investigate their performances, the porosity and back-to-back configurations are applied under light and heavy loading scenarios. A comprehensive comparison between preemption and non-preemption modes is made in each evaluation scenario. Finally, the AVB-OBTTW findings are compared with the previous related works.

Chapter 7 concludes the thesis and recommends some future research directions.

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