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 SURVEY

A Survey of Scheduling Algorithms for the Time-Aware Shaper in Time-Sensitive Networking (TSN)

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ABSTRACT Time-Sensitive Networking (TSN) is an enhancement of Ethernet which provides various mechanisms for real-time communication. Time-triggered (TT) traffic represents periodic data streams with strict real-time requirements. Amongst others, TSN supports scheduled transmission of TT streams, i.e., the transmission of their frames by end stations is coordinated in such a way that none or very little queuing delay occurs in intermediate nodes. TSN supports multiple priority queues per egress port. The TAS uses so-called gates to explicitly allow and block these queues for transmission on a short periodic timescale. The TAS is utilized to protect scheduled traffic from other traffic to minimize its queuing delay. In this work, we consider scheduling in TSN which comprises the computation of periodic transmission instants at end stations and the periodic opening and closing of queue gates. In this paper, we first give a brief overview of TSN features and standards. We state the TSN scheduling problem and explain common extensions which also include optimization problems. We review scheduling and optimization methods that have been used in this context. Then, the contribution of currently available research work is surveyed. We extract and compile optimization objectives, solved problem instances, and evaluation results. Research domains are identified, and specific contributions are analyzed. Finally, we discuss potential research directions and open problems.

INDEX TERMS Time-sensitive networking (TSN), time-aware shaper (TAS), scheduling, optimization, ethernet bridging.

I. INTRODUCTION

Modern applications, e.g., Industry 4.0 factory automation and motion control, demand highly deterministic network service. Exceeding latency and jitter bounds can result in immediate degradation of manufacturing quality or endanger health of machinery and operators. Some of these applications have to exchange data streams with precise timing to keep application-specific deadlines. Time-Sensitive Networking (TSN) is an emerging technology which enhances Ethernet networks with real-time properties. In TSN, talkers send uni- or multicast streams, called streams, to traffic sinks,

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called listeners. The network admits streams and guarantees quality of service (QoS). Time-triggered (TT) traffic constitutes periodic data streams with real-time requirements such as bounded latency or jitter. The transmission times of TT streams at their respective talkers must be scheduled such that excessive queuing in the network is avoided and their requirements are met. Although TT traffic has high priority, it can be delayed by low-priority frames in transmission blocking links for short time. To ensure that links are not occupied by low-priority traffic when needed for TT traffic, the standard IEEE Std 802.1Qbv [6] introduces an enhancement for scheduled traffic. The Time-Aware Shaper (TAS) can be implemented with this enhancement. It defines periodic time slices during which queues may send traffic to an output port and delays

TABLE 1. Surveys covering related topics to this paper.

Paper	Date	References	Focus	# Common referenced papers with this survey
Nasrallah <i>et al.</i> [1]	2018	407	Overview of TSN, DetNet, and 5G standards	14
Minaeva <i>et al.</i> [2]	2021	126	Scheduling in periodic systems	6
Seol <i>et al.</i> [3]	2021	207	Broad overview of TSN	29
Deng <i>et al.</i> [4]	2022	128	Broad overview of all topics related to AVB and TSN	17
Gavriliuț <i>et al.</i> [5]	2023	88	History of real-time Ethernet technologies, problem statements and solving techniques for various network design problems	13
This paper	2022	139	Traffic scheduling in TSN with the TAS	-

the respective traffic. In TSN, the TAS is used to protect TT traffic from other traffic classes. Therefore, TSN requires that appropriate TAS time slices are scheduled for output queues on all switches, in addition to the transmission times of all TT streams at their talkers. This combination guarantees very short delays for TT streams in TSN.

Standardization does not yet cover methods for computing such schedules. However, the topic has been examined by many publications. These research works use different methods for schedule synthesis, evaluation, and objectives for optimization. We survey the currently available literature for TSN schedule computation. The paper focuses on publications published until March of 2023 about TSN schedule planning with the TAS. Works about stream scheduling related to other technologies than TSN or for other traffic shapers in TSN than the TAS are not covered in this survey.

A. RELATED SURVEYS

To the best of our knowledge, no other review covers scheduling algorithms for TSN as its main topic. In fact, there is no survey about scheduling for TT streams for Ethernet networks, regardless of the used standard. However, there are surveys which intersect with the content of this work. Table 1 compiles the focus and the relationship of these surveys to this paper.

Nasrallah *et al.* [1] survey standards for low-latency communication. Besides DetNet and 5G, they also give a tutorial on the TSN standards. They reference a small number of papers related to traffic scheduling in TSN. However, they do not elaborate on their content as scheduling is not the focus of this work. Thus, only the most seminal works about scheduling from this time are referenced.

Minaeva *et al.* [2] give a literature summary for scheduling time-triggered real-time systems. They highlight research works from 1968 to 2020. As opposed to this work, they not only consider scheduling of streams in networks, but all systems with periodic schedules. Seminal works for TSN scheduling algorithms in the literature are mentioned, e.g., [7] and [8]. Out of 126 references, only 6 of them intersect with this work.

Deng *et al.* [4] review a wide range of topics about AVB and TSN from the literature of 2007 – 2021. Besides scheduling

approaches, they also give an overview of reliability and security modeling, and delay analysis in the mentioned areas. As a wider range of topics is covered, only a small part of the survey is concerned with scheduling. From the 128 discussed works, 17 works intersect with this survey.

Seol *et al.* [3] review TSN as a whole. The authors cover publications of the years 2014 – 2020. An overview of active research directions is given, including computing routings and schedules in TSN. Not only the literature about scheduling for the TAS is summarized, but also work concerned with other queuing mechanisms, hardware, and simulation frameworks. Therefore, only a small fraction of the literature about scheduling for TAS-based queuing in TSN is surveyed. They cover 207 research works, of which 29 are included in this work. Because of the wide range of topics covered, these works are referenced for further reading but their content is not discussed.

The recent survey of Gavriliuț *et al.* [5] gives an excellent introduction in the history of real-time Ethernet technologies. Additionally, they present typical problems in the design of networks for time-critical applications, e.g., scheduling, routing, worst-case delay analysis, topology synthesis, and bandwidth allocation. Seminal works for each of these problems are reported and summarized. Important results are recalled. However, the focus is much broader than the scheduling problem for the TAS. Thus, many works about scheduling were not covered.

B. CONTRIBUTION

In contrast to the mentioned surveys of Table 1, we focus on papers about scheduling algorithms and related topics which use the TAS. This survey claims the following contributions:

- We give a tutorial on TSN basics.
- We define the TSN scheduling problem for TAS and modifications to it. Additionally, we introduce common solution methods used in the literature
- We survey currently available TSN literature about scheduling for the TAS.
- We identify research directions, categorize the available literature, and highlight contributions to these topics.
- We compare the available algorithms and the presented evaluations to derive open research questions in this area.

C. SURVEY STRUCTURE

This paper is structured as follows. In Section II we present a brief introduction to TSN with a special focus on the TAS. Then, we formally define the scheduling problem in TSN and give a tutorial to common solutions methods from literature in Section III. Section IV gives an overview of the state-of-the-art of TSN scheduling and categorizes the presented literature. Section V compares the presented research work with regard to modelling assumptions, optimization objective, problem instances and scalability. Furthermore, we present the publication history of the surveyed literature in Section VI. We discuss issues and open research questions in Sections VII. Finally, we conclude the paper in Section VIII.

D. LIST OF FREQUENTLY USED ACRONYMS

The following acronyms are used in this paper.

ASAP	As Soon As Possible.
AVB	Audio Video Bridging.
BE	Best Effort.
CBS	Credit-Based Shaper.
CP	Constraint Programming.
CQF	Cyclic Queuing and Forwarding.
GA	Genetic Algorithm.
GCL	Gate Control List.
FIFO	First-In-First-Out.
FRER	Frame Replication and Elimination for Reliability.
gPTP	generalized Precision Time Protocol.
GRASP	Greedy Randomized Adaptive Search Procedure.
ILP	Integer Linear Programming.
OMT	Optimization Modulo Theories.
PBO	Pseudo-Boolean Optimization.
PSFP	Per-Stream Filtering and Policing.
QoS	Quality of Service.
SMT	Satisfiability Modulo Theories.
SRP	Stream Reservation Protocol.
TAS	Time-Aware Shaper.
TSN	Time-Sensitive Networking.
TT	Time-Triggered.
VLAN	Virtual LAN.

II. FOUNDATIONS OF TSN

TSN is a set of standards for deterministic data transmission with real-time requirements over Ethernet networks. In this section, we present a short tutorial about TSN. First, we present AVB based on which TSN was developed. Then, we introduce TSN with a special focus on scheduling and the TAS.

A. AUDIO VIDEO BRIDGING

Historically, multimedia equipment was interconnected with half-duplex point-to-point links for data transmission. These links were often dedicated to a single purpose, i.e., the transmission of one specific data stream. This results in a large

number of links which is expensive, hard to maintain, and error prone. Switched computer networks solved these problems. The most widely adopted technology for switched local area networks today is Ethernet. However, professional audio and video applications need bounded latencies and jitter, i.e., real-time guarantees for data streams. Switching in Ethernet networks was not designed for real-time transmissions. Therefore, the Audio Video Bridging (AVB) task group of the IEEE was founded to develop a standard to meet the requirements of multimedia applications in switched Ethernet networks.

AVB is organized in standards for time synchronization, admission control, and traffic shaping.

1) TIME SYNCHRONISATION

Network devices need a common understanding of time to ensure that all end stations in a network are able to coordinate their actions. Every AVB-capable device is equipped with a clock. The standard IEEE 802.1AS [9] defines a protocol to synchronize the clocks of all devices in an AVB network. This protocol is based on the *Precise Time Protocol* (PTP) introduced in IEEE 1588 [10] and is denoted as *generalized Precise Time Protocol* (gPTP). The gPTP defines an algorithm to select a so-called *Grandmaster* among the participating nodes of the protocol. The internal clock of the Grandmaster is used as reference clock. All other devices synchronize their clocks to the clock of the Grandmaster with time information sent from the Grandmaster. Intermediate nodes adjust the received time information to compensate propagation delays, processing delays, and different clock speeds before retransmitting them. The gPTP allows sub-microsecond precision for devices with at most seven hops distance to each other. This is needed for applications running on different end stations to synchronize their actions.

2) ADMISSION CONTROL

The Stream Reservation Protocol (SRP) introduced in IEEE 802.1Qat [11] allows senders of periodic data streams, denoted as *talkers*, to reserve bandwidth in a multi-hop Ethernet network. A talker which wants to send data advertises a new data stream to its connected bridge. This advertisement contains information about bandwidth and real-time requirements, the periodicity of the stream, and the destination MAC address. The destination may be a multicast group. The bridge forwards the advertisement if the requested resources are available. Worst-case latencies are calculated at every bridge. When the request reaches the destination of a data stream, denoted as *listener*, the listener acknowledges that it is ready, and the bandwidth is reserved along the path.

3) TRAFFIC SHAPING

Traffic shaping is the generic term for techniques that distribute packet transmissions in time. The AVB working group defines the so-called *Credit-Based Shaper* (CBS) in IEEE 802.1Qav [12]. It can be leveraged to smooth out bursts such

that receiving devices are not overwhelmed. This reduces buffering and congestion in the network. The CBS is a leaky bucket traffic shaper with at least two FIFO queues for two traffic classes. These classes are denoted as class A and class B. Both queues have a credit measured in bit. Dispatching and transmitting a frame from a queue is only allowed if the credit of the respective queue is non-negative. Credit increases linearly during times no frame is transmitted and decreases linearly during transmissions. Latency bounds for streams can be guaranteed by using a special configuration for the CBS defined in IEEE 802.1BA [13]. These are specific to the requirements of the AVB domain, guaranteeing 2 ms and 50 ms for class A and B traffic in networks with at most 7 hops. However, the average delay of a frame increases to up to 250 μ s per hop in the worst case when the CBS is used.

B. TIME-SENSITIVE NETWORKING

Ethernet networks are used in a wide range of industrial use cases as Ethernet is cheap and easy to implement. However, use cases such as industrial automation, in-vehicle communication or avionics have hard real-time requirements and need reliability. Data streams not meeting their deadlines may not only be worthless but impose safety risks. The latency guarantees and average delays offered by AVB fail to comply with the requirements of such use cases.

Time-Sensitive Networking (TSN) is a set of standards enhancing AVB for deterministic and reliable transmission of data over switched Ethernet networks. TSN is currently developed in the IEEE 802.1 TSN task group and adds new mechanisms for scheduling, traffic shaping, path selection, stream reservation, filtering and policing, and fault-tolerance. Most of the standards are enhancements of IEEE 802.1Q [14] which defines bridges and Virtual LANs (VLANs). We give a brief tutorial on the standards and mechanisms relevant for the scope of this survey, i.e., traffic scheduling in TSN with the TAS.

1) SIMILARITIES TO AVB

Similar to AVB, every device in TSN is equipped with a clock. TSN also uses the gPTP defined in IEEE 802.1AS [9] to synchronize clocks of all network devices. The CBS and an enhancement of the SRP are also part of TSN.

2) PATH SELECTION

TSN introduces a new mechanism for path selection in IEEE 802.1Qca [15]. In contrast to traditional Ethernet networks, it is not necessary to use Spanning Tree Protocols or Shortest Path Bridging. Paths can be computed by an arbitrary algorithm and are only limited to be trees. Thus, frames can be forwarded on an arbitrary path. Forwarding information of these so-called Explicit Trees are distributed with the Intermediate System to Intermediate System (IS-IS) protocol and stored in bridges. The Explicit Tree for the forwarding of a frame is determined by the MAC address of the root bridge of the Explicit Tree and the VLAN ID in the frame's header.

3) PRIORITIES

Every egress port of a TSN bridge is equipped with up to eight egress queues. These queues are First-In-First-Out (FIFO) queues. They correspond to the eight VLAN priorities defined in IEEE 802.1Q [14]. The VLAN tag in the header of an Ethernet frame determines the egress queue in which the frame waits for transmission. Every queue is equipped with a so-called Transmission Selection Algorithm (TSA). The TSA signals whether a frame is ready for transmission to a transmission selection mechanism. A possible implementation for a TSA is the CBS which allows frame transmissions only when the credit is positive. This selection mechanism selects the next queue from which a frame is dispatched and sent. TSN uses strict priority as transmission selection, i.e., the next frame is dispatched from the highest priority queue which signals a frame is ready for transmission.

4) FRAME PREEMPTION

High-priority traffic can be delayed due to conflicts with lower-priority traffic. IEEE 802.1Qbu [16] describes a mechanism for frame preemption in TSN which reduces such delays. Traffic is divided into preemptable frames and so-called express frames. The transmission of preemptable frames is paused and finished later if an express frame is ready for transmission. Consequently, a preempted frame is divided into fragments which are reassembled by the receiving node. The minimum size of a frame fragment is defined to be 64 byte. However, every fragment of a frame except for the last one has a trailer containing a 4 byte check sequence for error detection. Therefore, a frame can only be preempted after at least 60 byte were transmitted and the last 63 byte of a frame cannot be preempted.

5) RELIABILITY AND THE FILTERING OF DUPLICATES

Bridging in classical Ethernet networks assumes that no frames are duplicated and therefore no duplicates must be filtered. However, safety critical applications may require protection against frame loss and permanent link failures. IEEE 802.1CB [17] introduces a mechanism which allows to send multiple copies of the same frame, possibly over disjoint paths, and to eliminate duplicates. Thus, only a single copy of the same frame is forwarded or delivered to a higher layer on an end station. This mechanism is denoted as Frame Replication and Elimination for Reliability (FRER).

6) TRAFFIC SCHEDULING

Time-triggered (TT) traffic, also denoted as *scheduled traffic*, consists of periodic data streams with hard real-time requirements such as bounded latency and jitter. The properties of TT streams such as period, maximum frame size, frames per period, as well as the range of possible transmission offsets from their respective talkers, are known in advance. The transmission times of these streams at their respective talkers can be controlled and must be coordinated to ensure that all streams meet their real-time requirements. The computation

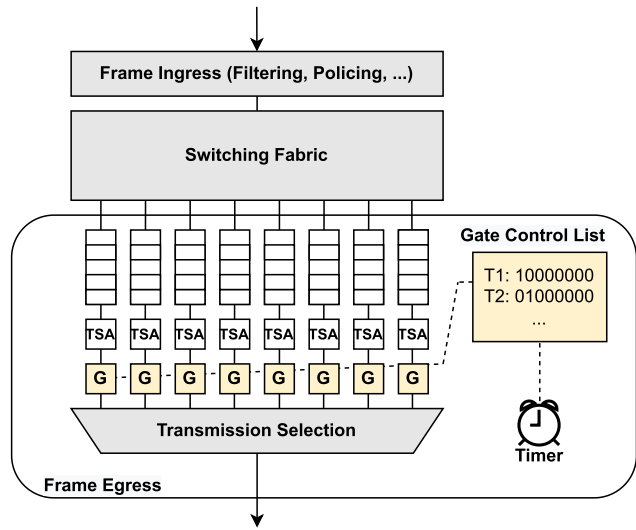


FIGURE 1. Path of a frame through a bridge. The egress port implements the enhancement for scheduled traffic. Every such egress ports has eight egress queues guarded by a transmission gate (G). The GCL controls the timed opening and closing of these gates.

of their periodic transmission times is denoted as *traffic scheduling*.

a: TRAFFIC SHAPING

TSN introduces new traffic shapers in addition to the CBS. An example for another shaper which can be used instead of the CBS is Cyclic Queuing and Forwarding (CQF) defined in IEEE 802.1Qch [18]. Time is divided into slots of predefined length. The length of a slot is denoted as cycle time. Bridges buffer all frames received during a slot and transmit them in the subsequent slot. Thus, stream latencies can easily be calculated from the cycle time and the number of hops.

IEEE 802.1Qbv [6] defines an enhancement for scheduled traffic. It can be leveraged to implement the Time-Aware Shaper (TAS). The TAS allows protecting TT traffic from other traffic such as AVB traffic or best-effort (BE) traffic. Additionally, the transit of TT streams through a network can be scheduled. Every egress queue has a so-called *transmission gate* or simply *gate*. Gates are either open or closed. Frames can only be dispatched and sent from an egress queue if the respective gate is open. The closing and opening of a gate is controlled by a so-called Gate Control List (GCL). A GCL entry consists of a time interval $[T_i, T_{i+1}]$ and a bit-vector. The bit-vector indicates which gates are opened or closed during the time interval $[T_i, T_{i+1}]$. Therefore, a GCL entries defines a time slice exclusively available to traffic with a priority corresponding to an open queue. These GCLs are executed periodically for an indefinite number of times. The computation of GCLs and appropriate cycle times, i.e., periods of these GCLs, is denoted as *scheduling* or *GCL synthesis*. The number of available GCL entries in an egress port is limited and depends on the used bridge. Figure 1

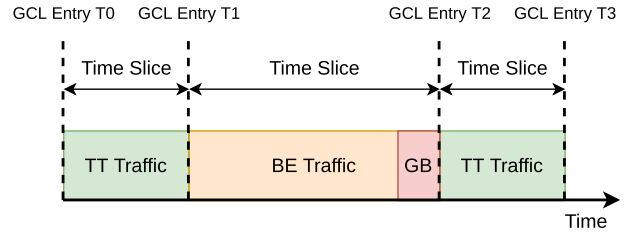


FIGURE 2. Time slices, GCL entries, and guard bands. The duration of a guard band may not be available for BE traffic as a frame can only be sent if transmission finishes before the respective gate is closed.

depicts the architecture of a typical TSN bridge according to IEEE 802.1Q [14], including the components of the TAS.

The TAS can be used to protect traffic by scheduling the GCLs accordingly.

b: GATE CLOSINGS AND GUARD BANDS

If the transmission of a frame is not finished until the end of the time slice the transmission started, a frame in the next time slice may be forced to wait until transmission finishes. Thus, it would be possible that a frame of a TT stream must wait because of a frame of BE traffic. This problem is avoided in TSN. Bridges detect automatically whether a frame transmission would conflict with a gate closing and hold conflicting frames back in this case. A guard band is a time interval with the length of the transmission of a maximum sized standard Ethernet frame. The duration of a guard band at the end of a time slice may not be available for transmissions to comply with closed gates. However, we emphasise that guard bands in TSN are implicit, i.e., they must not be configured explicitly. Transmissions may even start during a guard band if the transmission finishes before the next gate closing. Figure 2 depicts a guard band which restricts the transmission of BE traffic before the respective gate is closed. If frame preemption is used, the maximum size of a frame that cannot be preempted is 123 byte. This is due to the minimum size of a frame fragment, i.e., 60 byte of the frame and an additional 4 byte check sequence. A frame with 123 byte cannot be preempted until the first 60 byte are transmitted as the resulting first fragment would be too small otherwise. However, the last 63 byte also cannot be preempted as the resulting last fragment would be too small. Therefore, guard bands can be reduced to the length of a transmission of 123 byte if frame preemption is used.

c: SCHEDULER VS. TRAFFIC SCHEDULING

The term *scheduler* is sometimes used as a synonym for *traffic shaper*. For instance, the CBS and the TAS are schedulers in this terminology. Unfortunately, the term *scheduler* has also another meaning in the context of this survey. Many research works denote algorithms to plan GCL entries and frame transmissions in time with the TAS as schedulers. To avoid confusions, we will only use the second meaning in the remainder of this paper, i.e., a scheduler is a scheduling algorithm for the TAS. There are research works that use

the first meaning in their title or abstract or cover scheduling algorithms for other traffic shapers in TSN, e.g., Cyclic Queuing and Forwarding (CQF). Thus, these works give the impression that they are in the scope of this survey, e.g., [19], [20], [21], [22], [23], [24], [25], [26], and [27]. However, we remark that this survey only covers research works about scheduling algorithms and the scheduling problem for the TAS. Therefore, we do not discuss works which propose new shapers, i.e., new *schedulers*, or analyse other shapers than the TAS.

The challenge in planning a TSN network is to compute the schedules that coordinate the transmission times for all streams at their respective talkers and the GCLs of bridges such that the requested real-time requirements of all TT streams are met. This problem is formally defined in the next section.

III. THE TSN SCHEDULING PROBLEM

First, we introduce a common network model, relevant properties of TT streams, and the definition of schedules. Second, we state constraints for valid schedules. Then, we discuss scheduling and optimization in the context of TSN and the computational complexity of these problems. Furthermore, we present common problem extensions solved in the literature. Finally, we give an introduction to common solution techniques that have been applied to the scheduling problem.

A. NOMENCLATURE

A node of a TSN network is an end station or a TSN-capable bridge. End stations are sources and destinations of data streams. Bridges switch frames based on their header. We remark that a node may be a bridge and an end station at the same time, i.e., it implements bridging capabilities and is an end point of data streams. Links are full-duplex Ethernet connections between an end station and a bridge or between two bridges. TSN bridges are inevitably subject to multiple delays. These delays must be considered to ensure deterministic transmissions according to a schedule. The processing delay of a bridge is the time between a frame arrives at an ingress port, and it is put in an egress queue. The transmission rate of an egress port is the rate at which data can be transmitted over a link. The propagation delay of a link is the time needed for electrical signals to traverse the link. The queuing delay of a frame is the time the frame waits in an egress queue for transmission. Ethernet uses a preamble before of a frame transmission to signal a new transmission starts, and an inter-frame gap between two frame transmissions to ensure that the receiver can process a new frame. The maximum size of a frame in TSN is 1542 byte, including inter-frame gap and preamble. A TT stream is a periodically repeated data stream with real-time requirements. Every stream has a talker as source and possibly multiple listeners as destinations. The earliest and latest transmission offsets describe the time range during which a talker can start transmission relative to the start of a period. The deadline of a stream is the time at which all frames of the stream must have arrived at all destinations,

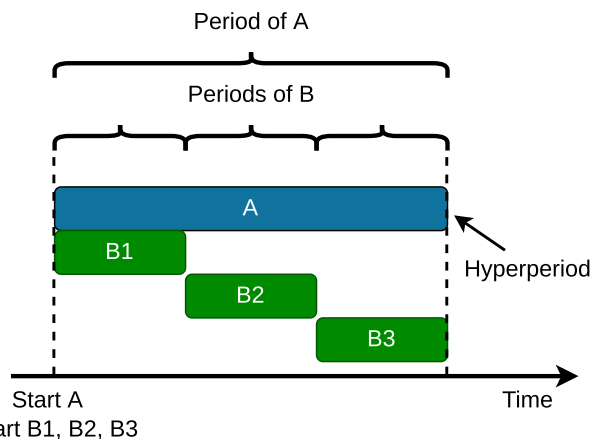


FIGURE 3. The period of stream A is three times the period of stream B. For modelling purposes, the hyperperiod is introduced, i.e., all streams are assumed to have that larger period. To cover the full duration of the hyperperiod, B is modelled by three consecutive copies B1, B2, and B3.

also relative to the start of a period. The entire payload of a stream must be delivered before the deadline. The payload of a stream may be sent with multiple frames.

The hyperperiod H of a set of streams S is the least common multiple of the periods of the streams. Let $s \in S$ be a stream with period p_s . A schedule for all streams in S contains $\frac{H}{p_s}$ consecutive replications of s , each having the hyperperiod as period. Scheduling algorithms typically consider transmission times, earliest and latest transmission offsets, and deadlines relative to the beginning of the hyperperiod. Figure 3 depicts an example with two streams A and B. The period of stream A is three times the period of stream B. A schedule for both streams thus contains only one period of stream A and three periods of stream B. A schedule for a set of TT streams in a TSN network consists of the transmission offsets of all streams at their respective talkers, and GCL configurations for all bridges. Transmission offsets of frames at bridges along their path follow implicitly. Schedules must be periodic, i.e., repeatable an indefinite number of times. The hyperperiod of a set of streams is the period of schedules for these streams.

B. SCHEDULING CONSTRAINTS

Given a problem instance for the TSN scheduling problem, i.e., a set of TT streams and a network topology. Every schedule which complies with the real-time requirements of all TT streams is considered a valid solution of the TSN scheduling problem. Such schedules are denoted as valid schedules in the TSN scheduling literature. The following constraints restrict the set of all possible schedules to the set of valid schedules.

1) BRIDGE DESIGN

TSN bridges are currently assumed to be store-and-forward bridges. Frames cannot be forwarded by a bridge before they have arrived at the egress queue. The duration of a transmission depends on the transmission rate of the sending egress

port, the size of the frame, and the propagation delay of the used link. The processing delay of the bridge must also be considered.

2) EXCLUSIVE LINK USAGE

No two frames can be in transmission over a link in the same direction at the same time.

3) DEADLINES

A stream meets its deadline when all of its frames arrive at the stream's destination before its deadline. For multicast streams, this holds for all destinations.

4) ROUTING

The frames of a stream follow some routing. Every instance of the same stream follows the same routing.

5) FRAME ORDER

There is no reordering of frames of the same stream. Frames that are sent earlier arrive earlier than frames sent later. This holds hop-by-hop and end-to-end. The source node of a stream sends frames of a stream in-order. There are no duplicates, i.e., a frame cannot be replicated by a bridge.

6) FIFO QUEUES

The order of frame arrivals at an egress queue must match the order at which frames are sent.

7) QUEUE SIZE

Frames of scheduled traffic must not be dropped for any reason.

8) GATE CONTROL

If a frame waits in an egress queue, it can only be sent when the respective gate is open. The gate must stay open until transmission finishes.

9) TRANSMISSION SELECTION

If multiple gates of an egress port are open and frames in the respective queues are waiting for transmission, the queue with the highest priority is the next queue to dispatch a frame.

10) ADDITIONAL FEATURES

Various modifications of the problem are presented in the literature. Additional constraints may be needed to model these problems. For example, multiple queues can be reserved for TT traffic per egress port. Queue assignment of streams must be modeled in this case. We discuss these problem modifications in Section III-E.

C. FINDING A SCHEDULE VS. OPTIMIZATION

There may be multiple schedules for a given problem instance. In fact, most problem instances have a large number of schedules as possible solutions. So far, the definition of the scheduling problem does not differentiate between

these solutions. A common way to compare solutions is to introduce an objective function. Such a function maps solutions to real numbers. The solution to an optimization problem is the schedule which minimizes or maximizes the objective function, i.e., has a smaller or larger objective value than any other schedule. Examples for objectives are minimizing end-to-end delays or jitter of TT streams. Another possible objective is minimizing the flowspan, i.e., the duration such that all frames have arrived at their respective destinations.

D. COMPUTATIONAL COMPLEXITY

The problem of deciding whether there is a valid schedule for a set of TT streams in a TSN network is known to be NP-complete [7] in general as Bin Packing can be reduced to it. This even holds without queuing [28]. NP is a class of decision problems, i.e., contains only problems which can be answered by either *yes* or *no*. Finding a schedule or finding an optimal schedule are not decision problems. Therefore, they are not contained in NP. However, they are computationally at least as hard as the question whether there is a schedule.

E. PROBLEM EXTENSIONS AND RESTRICTIONS

The definition of the basic problem in Section III-B only describes the common properties of the problems in the literature reviewed in this survey. Much research work focuses on special cases or problem extensions with additional constraints. This section introduces these problem variations in a general way such that they are clear in the remainder of this survey.

1) JOINT ROUTING

The definition of Section III-B assumes that the routing of every stream is a predefined part of the input and fixed. Much research work is dedicated to a variation of the scheduling problem with joint routing, which relaxes this assumption. In contrast to the basic problem, the routing of streams is variable and computed simultaneously with the schedule. This gives the scheduling algorithm more flexibility, as streams can be routed to omit heavily loaded links and thus conflicting scheduling constraints. A common approach is that the algorithm gets a set of possible paths as input for every stream, and it selects one per stream as the stream's routing. Other algorithms select arbitrary paths. Both approaches are possible due to IEEE 802.1Qca [15] as the standard allows arbitrary paths to be configured for every stream.

2) RELIABILITY

Research work dedicated to joint routing and scheduling can take reliability considerations into account. Such works define a model of possible faults and their probabilities. Scheduling algorithms can compute schedules which meet the real-time requirements of all streams with high probability for a given fault model. These schedules are denoted as robust schedules relative to a given fault model. For instance, scheduling approaches can compute schedules which are

robust against single link failures. This can be achieved by introducing redundant streams with the same payload and routing them through disjoint paths.

3) GCL SYNTHESIS

GCLs for all egress ports must be constructed. One possible approach is to open the gates for scheduled traffic at the beginning of a hyperperiod and never closing them. However, this approach comes with the drawback that no other queue can send. This may be necessary to protect other TT streams with tighter bounds by avoiding congestion in the queues for TT traffic.

Another common approach is to use a postprocessing scheme after scheduling transmission offsets, e.g., in [28] and [29]. GCLs are constructed such that the gate of a queue is opened when a transmission from this queue should start according to the schedule. The respective gate is closed when the transmission is finished according to the schedule. This approach allows a scheduler to use gates to delay frames. However, the number of available GCL entries is limited in real hardware bridges. Therefore, scheduling transmission offsets and synthesizing GCLs can also be considered in a joint scheduling algorithm instead of a postprocessing, e.g., in [30] and [31].

4) QUEUING

Queuing can cause serious problems for schedules of streams with real-time requirements [29]. Frames can get lost in non-deterministic events, such as link or end station failure. A frame missing in an egress queue may result in another frame being dispatched earlier than expected and scheduled. As a result, this frame may change the arrival order in some egress queue, ultimately resulting in a stream missing its deadline. Such problems can be avoided in two ways. First, by avoiding queuing at all. Second, by not allowing frames to wait in the same egress queue at the same time. In this way, it is not possible that some frame is dispatched earlier than scheduled due to a missing frame in an egress queue. These restrictions are not imposed by bridges according to IEEE 802.1Q [14]. Instead, they are considered during scheduling such that a scheduling algorithm only computes schedules robust against these non-deterministic events. In the following, we discuss problem extensions and restrictions from the literature.

a: UNRESTRICTED QUEUING

Allowing frames of different streams to be in the same queue at the same time is denoted as unrestricted queuing. Figure 4(a) depicts a schedule by showing frame arrivals and transmissions of a single bridge. The schedule shows two streams, A and B, with two frames per period. The queuing state is shown implicitly. A frame is queued at the same time with all other frames that arrive before the frame is transmitted. Thus, the frames A1 and B1 are in the egress queue at the same time. If A1 does not arrive according to

the schedule, e.g., due to a permanent link failure, B1 is transmitted earlier than scheduled. This is the case in the second period depicted in Figure 4(b). Consequently, B1 arrives earlier than scheduled in some other egress queue. This may result in some other frame experiencing more queuing delay than scheduled, ultimately leading to a missed deadline.

b: ISOLATION

The problems of queuing in case of non-deterministic events can be solved by not allowing frames of different streams to be in the same queue at the same time. If a frame is missing in a queue and no other frame is scheduled to be queued at the same time, no other frame can be transmitted earlier than scheduled. This approach is denoted as *frame isolation* in the literature. It was introduced in [29]. Figure 4(c) shows a schedule valid with frame isolation. If A1 does not arrive at the bridge, the schedule of B1 and B2 is unaffected.

c: NO-WAIT SCHEDULING

In no-wait scheduling, frames are dispatched and sent immediately after arriving at an egress queue. Queuing is not allowed. The rationale of this constraint is to avoid all consequences of non-deterministic events related to queuing. It was introduced to the domain of TSN in [28]. Figure 4(d) depicts a no-wait schedule for two streams. All frames are sent immediately after arrival. For example, B1 is received and transmitted after A1 and before A2 in the same period.

d: QUEUE ASSIGNMENT

Instead of restricting queue usage, the scheduling problem can also be extended by allowing more than one queue per egress port for TT streams [29], [31]. A scheduling algorithm for such a problem not only schedules transmission offsets and GCL entries, but also assignments of TT streams to egress queues. This is especially interesting with respect to frame isolation, as frames of multiple streams can simultaneously wait for transmission by the same egress port in different queues.

5) INTEGRATION OF AUDIO VIDEO BRIDGING

TT streams and AVB traffic can coexist in the same network at the same time. TSN bridges may support to use the CBS and the TAS in parallel according to [6]. TT streams and AVB streams compete for the same links, but use different queues in the egress ports. Therefore, the scheduling problem can be extended to also include a set of AVB streams as input. They are scheduled at their respective talkers, and considerations for the behavior of the CBS must be included during scheduling.

6) INTEGRATION OF BE TRAFFIC

BE streams have no real-time requirements, they are generally aperiodic and unknown a priori such that they cannot be scheduled. However, some schedules may be beneficial for BE traffic. For instance, large bursts of TT traffic within a long hyperperiod could be avoided to facilitate frequent

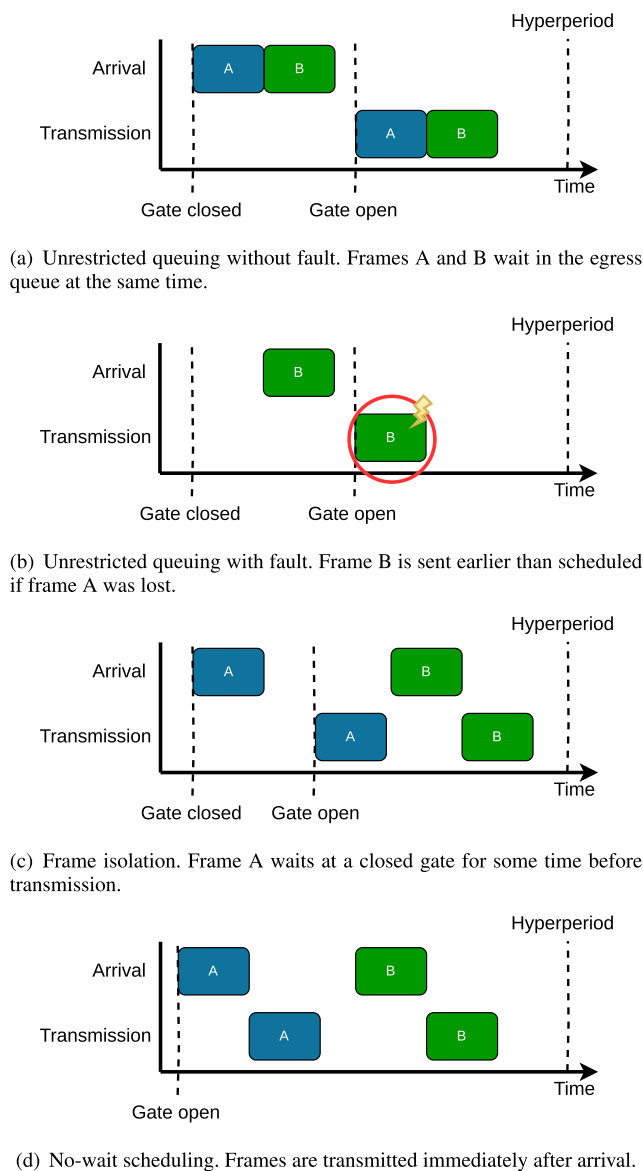


FIGURE 4. Queuing restrictions from TSN scheduling literature. Frame arrivals at an ingress port and transmissions at an egress port of the same bridge are shown. Processing delays are omitted to increase comprehensibility.

transmission opportunities for BE traffic, which may reduce the delay of BE traffic. Another example is avoiding GCL entries unless they save substantial capacity for other traffic. For each GCL entry, a guard band is needed within which frame transmissions cannot start. Therefore, compact schedules maximize capacity for BE traffic [28], [32].

7) DYNAMIC RECONFIGURATION

An entirely different problem related to the basic problem is dynamic reconfiguration of existing schedules. Such reconfigurations are necessary when streams are removed or new streams should be integrated into a schedule. While removing streams is rather easy, adding new streams to an existing

schedule can be complicated for two reasons. First, the transmission offsets of already scheduled streams may have to be changed. Second, links and egress queues are occupied by earlier scheduled streams, which places constraints on possible transmission offsets for new streams. The runtime of a scheduler during reconfiguration must be very low in many scenarios, such as in automotive use cases [33]. This is due to fast changing real-time requirements and traffic patterns of safety-critical applications. Recomputing the whole schedule with offline algorithms may be computationally infeasible in such cases.

8) MULTICAST

Streams in bridged Ethernet networks can be multicast streams according to [14]. Multicast streams have more than one listener as destinations. Therefore, the routing of a multicast stream is a tree. A multicast stream can be modelled by a set of unicast streams. However, only a single copy of a frame is transmitted per hop in TSN. Thus, this modelling is not appropriate. Scheduling algorithms may contain considerations for multicast streams instead of assuming all streams to be unicast. Joint routing approaches must compute trees instead of paths for every stream.

9) TASK SCHEDULING

Tasks are applications running on end stations. They are executed periodically. Their execution depends on data received via TT streams. Additionally, they can send TT streams after they processed some received data. Scheduling algorithms for TSN can schedule tasks and TT streams in a joint approach.

F. OPTIMIZATION METHODS

We classify the scheduling algorithms in the literature in exact and heuristic approaches. Exact approaches compute a schedule, or an optimal schedule if an objective is given, if one exists, or prove the problem instance infeasible. Heuristic approaches do not guarantee to find an optimal schedule. Instead, they try to find reasonably good solutions within short time. In the common case, they cannot deduce whether a problem instance is infeasible, nor is finding a solution guaranteed if one exists. In this section, we introduce common solution techniques and explain their basics.

1) EXACT APPROACHES

As the Scheduling Problem for TSN is NP-complete, there is probably no polynomial-time algorithm to compute TSN schedules. Therefore, it is reasonable to rely on the advances of the past decades in mathematical and combinatorial optimization. All exact solution approaches in the literature are based on the following four techniques.

a: INTEGER LINEAR PROGRAMMING

An Integer Linear Program (ILP) describes the space of possible solutions to a problem with linear inequalities. Every assignment of variables which fulfills all inequalities

$$\begin{aligned} &\min 2x + 3y - z \\ \text{s.t. } &4x + 3y \leq 7 \\ &x - 2z \leq 4 \\ &3y + 2z \leq 10 \end{aligned}$$

FIGURE 5. Example of an ILP model.

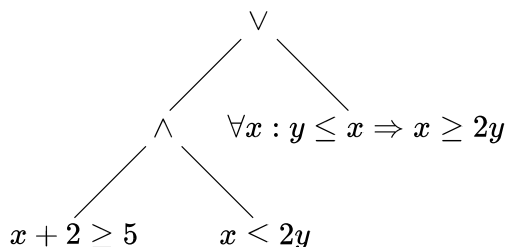


FIGURE 6. Example of a formula used in SMT solving. The basic structure is a formula from propositional logic, but predicates from other theories may be used as atomic formulas instead of Boolean variables.

corresponds to a solution of the problem and vice versa. Some variables may be restricted to take only integer values. A linear objective function may describe the quality of solutions. Figure 5 depicts an ILP which minimizes an objective function. ILP solvers compute a feasible assignment which minimizes the objective function. Every encountered solution in the solution process corresponds to an upper bound on the objective value of the optimal solution. Additionally, the solver can infer lower bounds for the objective value of the optimal solution during the solution process. So even when finding the optimal solution is not possible in reasonable time, ILP solvers yield estimations of the maximum gap to the optimum. Widely used state-of-the-art ILP solvers are CPLEX [34] and Gurobi [35].

b: SATISFIABILITY MODULO THEORIES

Satisfiability Modulo Theories (SMT) solvers find solutions to problems described by first-order formulas. Formulas model a problem with variables and predicates which are connected by logical operators. Besides Boolean variables, SMT solvers allow formulating predicates in other logical theories and use them as atomic formulas. SMT solvers have an interface for theory-specific solvers so that the problem can be modelled with the best suitable theory. Examples of theories are the theory of linear arithmetic with integers or the theory of bit vectors. Figure 6 depicts a formula with predicates from the theory of linear arithmetic with integers. The basic structure of a model is a formula from propositional logic, but predicates from integer arithmetic are used as atomic formulas.

The solver searches for an assignment of the variables that evaluate the formula to *true*. It uses techniques from SAT

solving to reason about satisfiability, combined with theory-specific solvers for conjunctions of predicates. SMT solving is only about finding some satisfying solution. When the best assignment regarding some objective function is computed, the term OMT is used. Z3 [36] is a widely used SMT solver which can also be used for optimization.

c: CONSTRAINT PROGRAMMING

Constraint Programming (CP) is a general solution approach to combinatorial problems. The set of feasible solutions to a problem is described in a declarative way. In this sense, ILP and SMT solving are special cases of CP solving. However, CP solvers use backtracking, local search, and constraint propagation techniques to solve CP models as opposed to ILP solvers. Another relevant case of CP is the restriction of variable domains to a finite set. CP-SAT is a widely used CP solver [37].

d: PSEUDO-BOOLEAN OPTIMIZATION

Similar to ILPs the solution space of a problem in Pseudo-Boolean Optimization (PBO) is modelled with linear inequalities, but all variables must be binary. However, instead of using mathematical optimization as in ILP solving, techniques from SAT solving like propagation and conflict refinement are employed. A linear objective function can be minimized by adding it as a constraint to the model with some bound. The solver is called multiple times with different bounded objective constraints. Every infeasible solver run gives a lower bound on the optimal objective values. Every solution yields an upper bound on the optimal solution. The optimal solution is found, with respect to some minimal precision, when the gap between lower and upper bound is smaller than the minimal precision provided by the user.

2) HEURISTIC APPROACHES

Because finding optimal solutions for realistic problem instances is infeasible in many cases, heuristic algorithms are used. Such algorithms are used to find suitable solutions in reasonable time, generally without knowing whether there are better solutions. Metaheuristic approaches are common algorithms that can be applied for a wide range of problems. Alternatively, there are heuristics that use problem-specific knowledge for many problems, and there may be combinations of both.

a: GREEDY RANDOMIZED ADAPTIVE SEARCH PROCEDURE

Greedy Randomized Adaptive Search Procedure (GRASP) is a metaheuristic which can be adapted to various problems. Its building blocks are a greedy-randomized algorithm to construct initial feasible solutions, and a local search algorithm. The greedy randomized algorithm incrementally constructs a solution by making random decisions among the set of decisions with the smallest increase in cost until a feasible solution is found. The local search explores neighboring solutions, i.e., solutions with minimal changes, to the intermediate

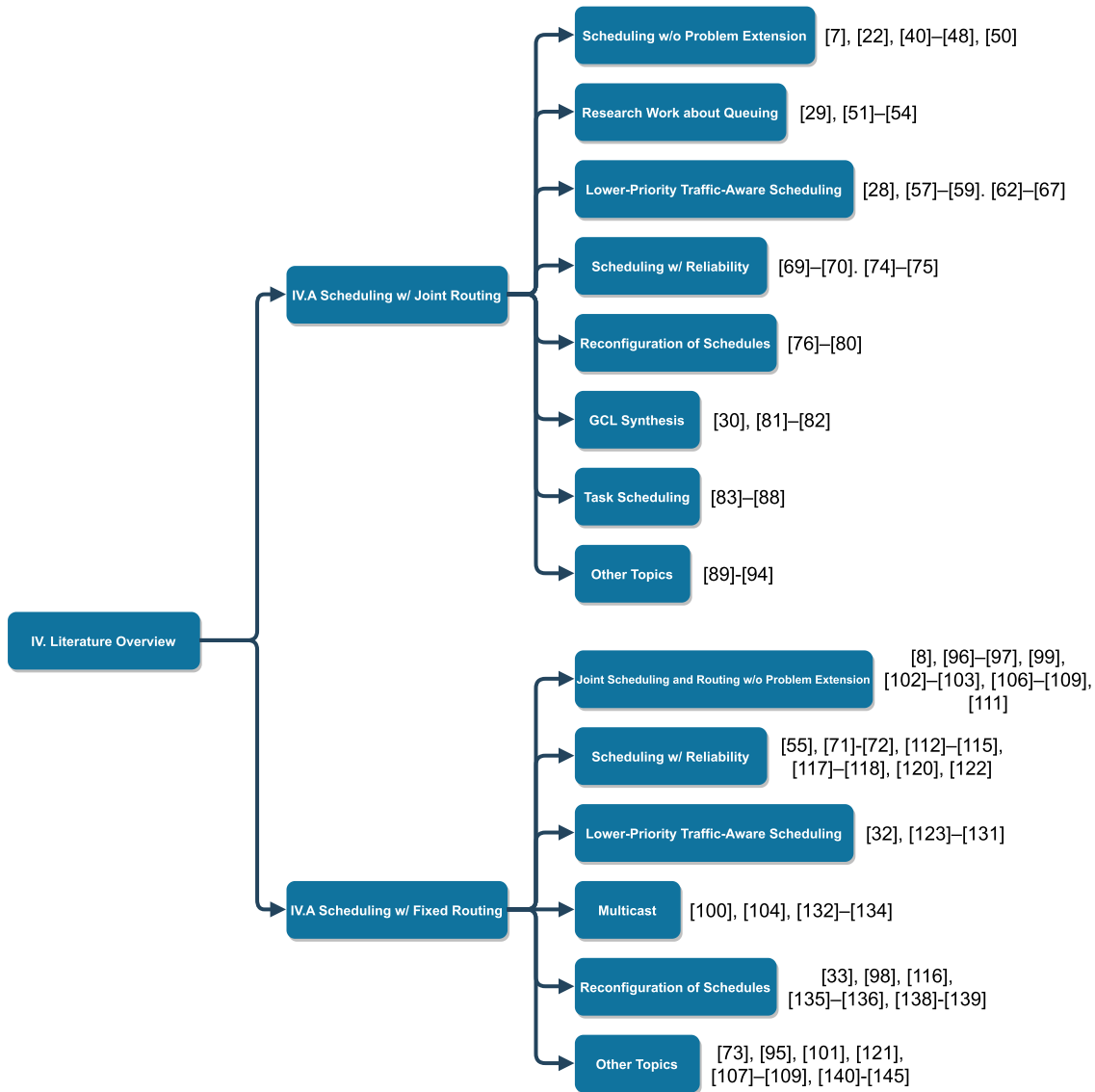


FIGURE 7. Classification of the surveyed research works in the scope of TSN scheduling.

solution. It explores the solution space until it finds a local optimum. Both steps are repeated a predefined number of times and the best encountered solution is returned. To adapt GRASP for a specific problem, a greedy randomized algorithm to generate initial solutions and a local search algorithm must be constructed.

b: TABU SEARCH

Tabu Search is a metaheuristic to systematically explore the solution space. It uses an initial solution as start and moves to the best neighboring solution. The algorithm keeps a tabu list of previously visited solutions or changes to solutions to avoid walking cycles in the solution space. Only neighboring solutions or changes to solutions which are not contained in the tabu list are considered for the move. The best encountered solution after a specific number of moves is returned.

To construct a problem-specific heuristic, a heuristic to generate an initial solution and a function returning the possible changes to some given solution must be built.

c: SIMULATED ANNEALING

Simulated Annealing (SA) is a metaheuristic used to find good approximations of the global optimum of an optimization problem. It is inspired by cooling processes in physics. A global variable for temperature is used. Temperature decreases slowly to 0 in discrete steps. In each step, a neighboring solution is randomly selected, and the objective function is evaluated. The probability of moving to a neighboring solution depends on the current temperature and the objective value of the considered solution. A move to a neighboring solution which is worse than the current solution is possible with small probability to escape from local optima.

As temperature decreases, the probability of moving to solutions with worse objective value vanishes. The best solution encountered after some acceptance criterion holds is returned. To adapt SA to a specific problem, a heuristic to generate an initial solution and a function returning the possible changes to some given solution must be built. Additionally, the way the temperature is decreased and the acceptance criterion must be selected.

d: GENETIC ALGORITHMS

Genetic algorithms (GA) are a metaheuristic approach inspired by evolution processes and natural selection in biology. Candidate solutions are considered as individuals. Chromosomes represent properties of these individuals and are coded into bitstrings. At every point in time, there is a pool of individuals, i.e., the population. New individuals are constructed from two or more existing solutions, i.e., genetic crossover is performed. Individuals may be altered randomly, i.e., their chromosomes are mutated. When transiting to the next generation, some individuals die and are removed from the population. The probability of dying for an individual depends on its fitness. The fitness function is the optimization objective of the modeled problem. The best individual encountered after some number of generations is returned. As in biology, high-quality solutions have a higher probability to survive and reproduce, which in terms yields new high-quality solutions. To construct a problem-specific heuristic, a heuristic to generate initial solutions must be constructed. Suitable crossover as well as mutation and selection mechanisms have to be used. Parameters like population size, stopping criterion, and probabilities for selection and mutation must be designed.

e: LIST SCHEDULING

List scheduling (LS) is a metaheuristic to schedule tasks on identical machines. The tasks are sorted in a list according to some measure of priority. In every step, the first task in the list is selected. If a suitable machine is available, the task is executed on this machine, otherwise the next task in the list is selected. These steps are repeated until all tasks are executed. Considering streams as tasks and end stations as machines yields a heuristic for TSN scheduling. A well-known heuristic from the scheduling literature can be considered to be special case of list scheduling. As-soon-as-possible (ASAP) scheduling orders streams by priority and schedules them one by one at the earliest possible time along their paths.

f: MACHINE LEARNING

Machine learning is the generic term for a wide range of methods. Tools from linear algebra, statistics, and probability theory are used to construct mathematical models that can make decisions or construct solutions to a problem. The construction of such a model is denoted as *learning* or *training*. Typically, it takes a large amount of time and computational effort to train a model, but answers to request can be obtained really fast afterwards. Examples of machine learning methods

are deep learning and reinforcement learning. However, the details of these methods are way beyond the scope of this survey. We refer to [38] and [39] for an introduction.

IV. LITERATURE SURVEY

In the following section, we give an overview of the literature about TSN scheduling. We categorize research work based on whether scheduling with fixed routing or joint routing is considered. Both sections are further grouped by the main topics of the respective papers. Comparability of techniques and results of research works in the same group is ensured by this classification. Figure 7 depicts this classification.

A. SCHEDULING W/FIXED ROUTING

We give an overview of research works which only deal with the scheduling of TT streams. In all papers presented in this section, the routing of TT streams is fixed and given as input to the scheduling algorithm. Such scheduling algorithms cannot change the routing during scheduling in case of conflicting streams. We group publications in categories based on similar topics, like model assumptions or problem extensions.

1) SCHEDULING W/O PROBLEM EXTENSIONS

We discuss publications solving the unmodified scheduling problem.

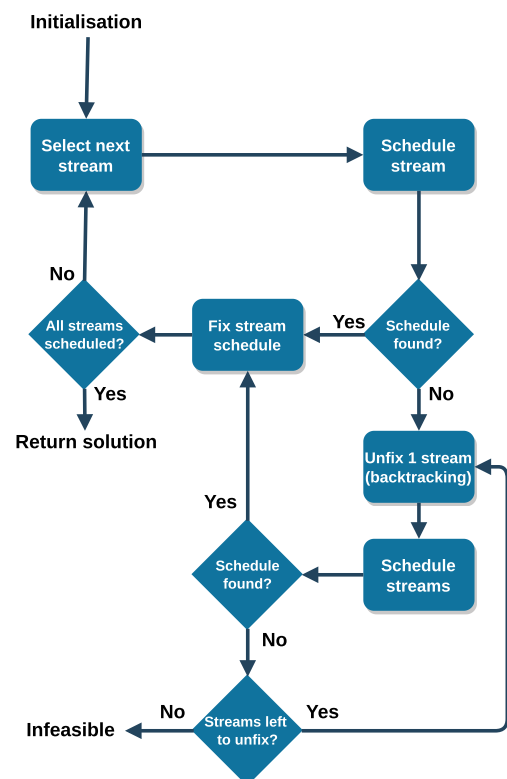


FIGURE 8. Incremental approach of Steiner [7]. Similar ideas were used by other approaches, e.g., in [29].

Early work about scheduling of TT traffic in Ethernet networks was conducted by Steiner [7]. Even though this

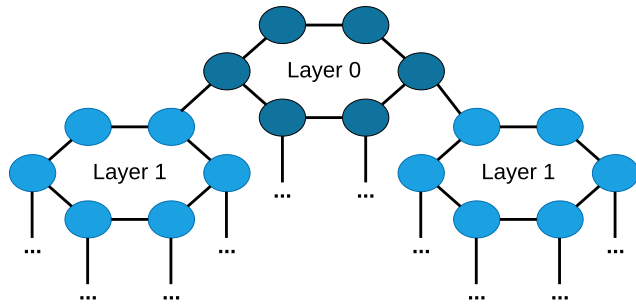


FIGURE 9. Multi-layered ring topology used in [40].

work is not specific to TSN, it influenced many research works covered by this survey. The author proposes the use of SMT solving for the scheduling of TT streams. An incremental approach is presented. Figure 8 depicts this approach. Streams are scheduled one after another. Schedules of already scheduled streams are fixed in later iterations. Backtracking is used in case of infeasibility, i.e., the schedule of some stream is unfixed and the stream is scheduled again simultaneously with the new stream. Backtracking is repeated until a schedule is found, or no stream schedules are left to unfix. This idea was adopted by many later works for TSN scheduling, e.g., [29] and [31].

Oliver et al. [31] give an SMT model based on mapping streams to transmission time windows of egress queues. The number of these transmission windows is fixed per egress port, and their placement and size is computed by the scheduling algorithm. As a side effect of using a fixed number of transmission windows, the number of gate events and thus guard bands is limited, even though the authors do not explore this matter. The authors use isolation to restrict the problems imposed non-deterministic behavior, e.g., frame loss. Two queues per egress port are dedicated for TT traffic. They evaluate the solving time of their approach with respect to the number of streams and the number of transmission windows per egress port. Their results indicate that the solving time increases exponentially with the number of streams. However, for reasonable numbers of streams and transmission windows, solving time is more sensible to the number of transmission windows. A comparison to the SMT from [29] shows that the window-based approach with one window per egress port is faster in finding a schedule. The average jitter is significantly reduced when the number of transmission windows per egress port is increased.

Steiner et al. [41] suggest the SMT model from [31] as a starting point for the standardization of TSN scheduling mechanisms. They demonstrate their model by reporting the same evaluation results as in [31] with a reduced number of transmission windows.

Hellmanns et al. [40] extend the Tabu Search algorithm of [28] for no-wait scheduling. They construct a 2-stage approach for hierarchical networks which consist of multiple rings on different layers. They argue that such topologies are

common in factory automation. Figure 9 depicts a model of such a topology. First, they schedule streams with talker and listener in the same ring. This step is done individually for every ring. No queuing is allowed in these schedules. Then, they simulate the transmission of all streams with end points in different rings as if they were sent at the same time from their respective talkers. No queuing restrictions apply to these streams, i.e., unrestricted queuing from Section III-E4.a is allowed. If all streams meet their deadlines in this simulation, the simulated behavior is used as schedule. They compare this approach with scheduling all streams at once with the Tabu Search algorithm. Their evaluations demonstrate that the proposed 2-stage scheduling scales better for problem instances with many streams compared to the original Tabu Search approach. The latter does not produce results for more than 1000 streams due to memory limitations. The 2-stage scheduling is two orders of magnitude faster in the special case of multi-layered ring topologies. The authors report that the number of needed GCL entries is significantly reduced by the 2-stage approach.

Another heuristic for no-wait scheduling is proposed by Zhang et al. [22]. They analyze how frame transmissions may conflict and derive the range of possible transmission offsets per frame. A comparison to the SMT of [31] and the ILP of [28] shows clear performance benefits of the proposed heuristic. The SMT was able to schedule about 300 streams, while the ILP scheduled about 1000 streams, and the heuristic scheduled 1200 streams in the evaluation scenario.

Kim et al. [42] give a heuristic algorithm to compute valid schedules, and a post-processing to reduce end-to-end delays. Streams are ordered by priority and are scheduled one after another. The individual frames of a stream are scheduled along the stream's path. The hyperperiod is divided into intervals and every frame is assigned to the earliest unoccupied interval. The presented evaluations indicate that end-to-end delays are reduced by up to one third per stream in the evaluation scenarios.

The authors of Kim et al. [43], [44] propose a genetic algorithm to schedule TT traffic in automotive scenarios. Genes encode the scheduling order of frames. Frames are scheduled as soon as possible according to this order and along the respective stream's path. The objective function used to compare scheduling orders is the weighted sum of end-to-end delays, jitter, and bandwidth utilization of the corresponding schedule. As in [28], a schedule compression algorithm is employed to reduce the bandwidth occupation of guard bands. The proposed approach outperformed random schedules regarding all three metrics in almost all evaluation scenarios. The approach from [42] is also outperformed with regard to the used objective.

Ansah et al. [45] present a scheduling algorithm in the special case of a line topology where all talkers converge in a single bridge. Based on this method, they also give an algorithm to compute GCLs in such a topology if the streams are schedulable.

The special case of an in-vehicle network with only a single hop is analyzed in [46]. They assume all traffic streams to be sent continuously and belonging to different traffic classes and egress queues. Essentially, they implement round robin traffic shaping with the TAS. However, we remark that real in-vehicle networks are more complex and thus the gained insights are limited.

The authors of [47] compare the suitability of a large set of metaheuristics for TAS scheduling. They maximize the number of scheduled streams for the same problem instance with various functions of a metaheuristic library. The authors observed the best results with math based and system based heuristics and interpret this as a hint for future research directions.

Vlk et al. [48] propose a heuristic algorithm to schedule very large-scale problem instances. The algorithm shares many similarities with the well known DPLL algorithm from SAT solving [49], e.g., probing, backtracking in the case of conflicts, and restarts. Frames are scheduled one by one. If a conflict arises, all decisions are reverted up to the conflicting frame. The authors compare the heuristic with SMT-, ILP-, and GRASP-based algorithms. The schedulability of an approach with respect to some set of problem instances is the fraction of solvable problem instances within some time limit. The proposed heuristic outperforms all other approaches regarding schedulability and solving time. In fact, they were able to schedule instances with up to 10812 streams in a tree-like topology with 2000 nodes. This result outperforms all other approaches in the literature. Evaluations with a real-world instance from avionics are also presented.

Wang et al. propose a deep reinforcement learning approach for no-wait scheduling in [50]. They train machine learning models for various network topologies. The model aims to reduce the maximum arrival time among all frames to reduce the number of guard bands. For networks with up to 9 bridges and 10 end stations, the authors report solving times of at most 400 s.

2) RESEARCH WORK ABOUT QUEUING

We highlight works which allow or deal with the implications of queuing.

Craciunas et al. [29] construct an incremental SMT model to schedule TT streams based on [7]. They define flow isolation and frame isolation as properties of a schedule to prevent some sources of non-determinism, e.g., single link failures. They present models to compute schedules with either flow or frame isolation. Besides isolation in the time domain, they also employ isolation in the spatial domain by the possibility of assigning different streams to different queues. The authors identified the problem of clock synchronization errors and introduce gaps between frame transmission to cope with this problem. They compare the effect of frame and flow isolation to the solving time of their SMT model. Their evaluations indicate that flow isolation reduces solving times compared

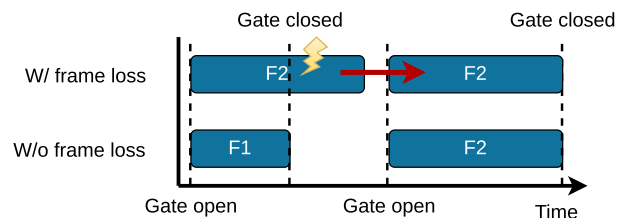


FIGURE 10. Size based isolation proposed in [53]. Frame transmissions from an egress port connected to an end station are shown. Assume F1 and F2 are scheduled to wait some time in the same egress queue. If the first frame F1 has not arrived at the egress queue, F2 cannot be transmitted in the time slice dedicated for F1 as it is too short.

to frame isolation. However, more problem instances can be scheduled with frame isolation.

Vlk et al. [51] investigate the effect of the isolation constraints from [29] on schedulability. When a frame is lost during transmission and does not reach the next egress queue as scheduled, another frame may be dispatched earlier than scheduled from this queue. This frame in turn can cause more non-determinism on its path. Not allowing frames of different streams to be in the same queue at the same time solves this problem, but reduces the solution space considerably. A modification for bridges implementing the TAS is proposed to cope with this conflict. Queues with this modification check whether the next frame is the correct one with respect to the schedule. If this is not the case, the queue idles until the next frame transmission is scheduled. A comparison shows clear benefits regarding schedulability. The number of streams which are scheduled to arrive before their deadline is also significantly increased compared to isolation models.

The authors of [52] present a heuristic to schedule streams with queuing. The heuristic is based on transmission windows similar to [31]. In contrast to earlier works which include queuing in their model [29], [31], they drop isolation constraints. Network calculus is employed for a worst-case end-to-end latency analysis. They minimize the occupation percentage of egress ports, i.e., the percentage of the hyperperiod which is reserved for TT traffic. In this way, long and frequent time intervals for lower-priority traffic are scheduled. Their evaluations indicate that their approach is superior regarding end-to-end delay and schedulability of streams compared to earlier works from the same authors.

Chaine et al. [53] use queuing for jitter control. They propose to schedule streams without queuing at all egress ports except for egress ports connected to end stations. Frames are buffered in these egress ports and are released such that jitter constraints are satisfied. The authors present a novel isolation approach, denoted as *size based isolation*. Frames must be buffered in increasing frame size order if they are stored in the same queue. Two GCL entries are used to close and open the corresponding gate between two frame transmissions. In this way, frames cannot be transmitted during an earlier time slice than scheduled if another frame is missing in the queue, as earlier time slices are too short. Figure 10 depicts such a scenario. The authors give an ILP model to

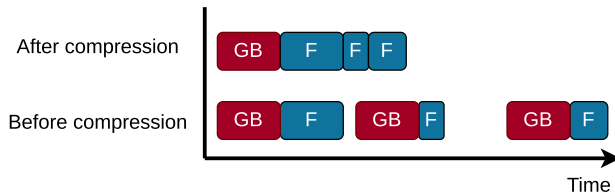


FIGURE 11. Effect of the schedule compression algorithm from [28]. Scheduled frame transmissions (F) and guard bands (GB) over a single link are shown.

compute schedules with their approach. A comparison of their approach to an unspecified approach for latency minimization demonstrates that their approach reduces scheduling time significantly. However, this comes with the cost of higher latencies.

Bujosa et al. [54] propose a heuristic scheduling algorithm which handles queue assignment of streams. Instead of scheduling frames or streams one after another on their entire path, they schedule all transmissions over a single link before scheduling the transmissions over another link. They present results about the scalability and schedulability of their approach compared to a CP approach from the literature [55]. Not surprisingly, scheduling is significantly slower with a CP approach compared to a heuristic.

3) SCHEDULING W/OTHER TRAFFIC

The schedule of TT streams may affect other traffic classes. AVB and BE traffic cannot be scheduled, but QoS metrics of these classes can be influenced when they are taken into account during the scheduling of TT streams. We summarize works with such considerations.

Dürr et al. [28] present an ILP and a Tabu Search algorithm to compute no-wait schedules for TT streams. They model the problem with job-shop scheduling, a widely used modelling framework in the scheduling literature. The authors measure the solving times of their Tabu Search and conclude that the network topology and size have no influence on solving times. They minimize the flowspan to construct a large time slice for BE traffic at the end of the computed schedules. They propose a compression algorithm as post-processing for schedules which aims to reduce the number of GCL entries needed to deploy a schedule. The authors note that this increases the available bandwidth for BE traffic as the number of guard bands is reduced. Figure 11 depicts the effect of the schedule compression algorithm. They report that the number of GCL entries can be reduced by 24% on average. Parts of the content of this work are also featured in the PhD thesis of Nayak [56].

The authors of [57] give an ILP to compute schedules for TT streams and additionally present a GRASP heuristic to schedule AVB streams. They restrict queuing by enforcing frame isolation. Their heuristic computes a routing for AVB streams such that they meet their deadlines. It reduces the search space by only considering a fixed number of shortest

paths for every pair of nodes as possible routings. The schedule of TT streams, computed by their ILP model, serves as input for the heuristic and cannot be changed. They compare their AVB routing with the naïve approach of always selecting the shortest path. The comparison demonstrates that more AVB streams can be scheduled with their approach. A comparison of solving times of their ILP to the SMT from [29] is conducted. They state that their proposed ILP does not scale well for industrial-size instances and further efforts to create a suitable heuristic are needed.

The authors of [58] propose an SDN-based method for traffic bandwidth allocation in safety-critical environments. While this work does not present a scheduling algorithm for the TAS, it gives a method to configure the CBS such that latency requirements of streams are met. They use a particle swarm optimization heuristic for this purpose. Evaluation results for the schedulability of stream reservation messages under varying network utilization by TT traffic are reported.

Santos et al. [59] present an extensive SMT-based modelling of the scheduling problem with openly accessible implementation. Their model contains a range of features known from previous works, e.g., transmission windows, multicast, guard bands, and bandwidth considerations for BE traffic which were not covered by a single approach in the past. The starvation of BE traffic is prevented by restricting a user-defined fraction of a hyperperiod exclusively to be used by other traffic which is related to the approach of minimizing the flowspan [28]. Additionally, unrestricted queuing is integrated which is uncommon in exact approaches so far. The authors mention the limitation of only one gate opening per queue per hyperperiod in the presented model which reduces the available bandwidth for other traffic classes. They evaluate their approach on a realistic sized network and report successful scheduling for up to 10 multicast streams. The model is also used in the well known simulation framework OMNeT++ [60]. The thesis of Santos [61] explains the model in detail.

Houtan et al. [62] compare schedules computed with various objectives for the same SMT model with respect to the QoS of BE traffic. They propose minimization and maximization of frame offsets, with the goal of increases the QoS by grouping frames together. Additionally, they also suggest two objectives which maximize the gaps between consecutive frame transmissions over a link. They integrate frame and flow isolation in their SMT model. Unfortunately, their work lacks a description which one was used in the evaluations. A comparison of the different objective functions indicates that larger gaps between frame transmissions of TT streams increase the QoS of BE streams. For instance, BE traffic may experience less starvation and average latencies are reduced. Figure 12 depicts how BE traffic may benefit from maximizing the gaps between TT frame transmissions. However, we note that the used system model features deadlines for BE traffic, and they measure the number of deadline misses, so a comparison with the other mentioned research works is

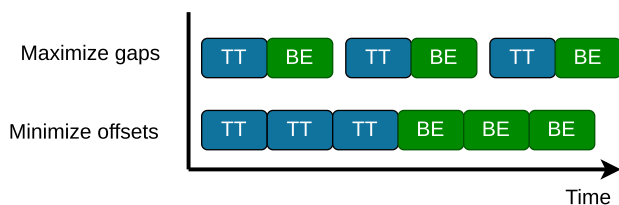


FIGURE 12. Effects of different objective functions to BE traffic in [62]. Frame transmissions of TT and BE traffic over a single link are shown.

not possible. The solving time for their SMT depends heavily on the objective function used.

The model of [29] is used for an in-vehicle scenario in [63]. The authors present simulation results with typical traffic patterns in such a scenario. They compare end-to-end delays for schedules using the TAS to schedules using the strict priority mechanism. Their results indicate that scheduling with the TAS can ensure real-time requirements of TT streams while the performance of lower-priority traffic is less affected compared to the strict priority mechanism.

Barzegaran et al. [64] give a CP approach to compute transmission windows for TT streams. In contrast to other window-based approaches [31], [41], they assume that not all end stations support TSN. They use a worst-case delay analysis to eliminate solutions that may violate the real-time requirements of the given problem instance. They compare their approach to the algorithms presented in [29], [31], [52], and [57]. They outperform these approaches in terms of solving time, but end-to-end delays and bandwidth utilization are significantly worse compared to [29] and [31]. They also perform simulation runs of their schedules with OMNeT++. The results indicate that their worst-case analysis for end-to-end delays holds but overestimates the simulated delays considerably.

The coexistence of the TAS and Cyclic Queuing and Forwarding (CQF) in TSN is investigated by Pei et al. [65]. They propose to use CQF for rate constrained traffic with deadlines, i.e., some egress queues per egress port are shaped by CQF. Streams of scheduled traffic and rate constrained traffic are scheduled simultaneously. They are scheduled one after another in least laxity first order, i.e., the next scheduled stream is the stream which deadline expires next. The same approach is used only for scheduled traffic streams as an alternative for comparison. The evaluation shows that the joint handling of scheduled traffic and rate constrained streams results in higher schedulability.

Another approach which combines the TAS and CQF is presented by [66]. They consider the scenario of multiple traffic classes with different real-time constraints. Besides of scheduled traffic with low latency and jitter requirements, there are also two other traffic classes with uncritical periodic streams and best effort traffic. The uncritical periodic streams are assigned by egress queues shaped by the CQF. The authors present a heuristic to compute a schedule for all traffic classes simultaneously. The evaluations show that sorting streams in

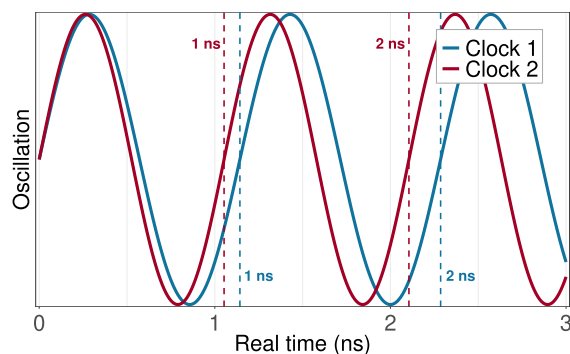


FIGURE 13. Timing signals of two clock oscillators. Clock 1 runs slower than clock 2. Therefore, the difference between both clocks increases over time.

earliest deadline first order before scheduling is beneficial for the schedulability. In contrast to that, sorting streams by frame size or period reduces schedulability considerably.

Wang et al. [67] propose a combined scheduling scheme for TT and AVB streams. AVB streams are shaped with CQF. They use guard bands to protect TT frames from AVB frames. Their heuristic tries to schedule as many AVB streams as possible while load balancing the traffic amount between the time slots of the CQF mechanism. The authors report that their approach significantly reduces jitter and solving times compared to another approach for CQF.

Huang et al. [68] propose a recursive scheduling heuristic using backtracking. They use a complex in-vehicle topology to evaluate their approach and also include AVB streams in the evaluation scenario. We highlight that they give detailed stream parameters which is rare for real-world use cases. They also include Frame Replication and Elimination for Reliability [17] to cope with frame loss of safety critical traffic. Additionally, an SMT model is presented and compared to their heuristic. The heuristic outperforms the SMT in regard to schedulability, scalability, and end-to-end latencies by far in the evaluation scenario.

4) SCHEDULING W/RELIABILITY

Reliable transmission of data streams is one of the design goals of TSN. Additionally, to hardware features ensuring reliability, schedules can be assembled to mitigate the effects of various faults. We discuss publications which take such considerations into account.

The clock frequencies of two clocks are not exactly equal for technical reasons. This results in so-called *clock drift*, i.e., clocks running with different speeds. Figure 13 depicts this problem. Craciunas et al. [69] extend their model from [29] to cope with clock drift during scheduling. They introduce a parameter for the maximum allowed clock drift into all equations which contain transmission offsets or reception times of frames. Effectively, they merely increase the gap between frame transmissions which is already contained in the model of [29]. Clocks are resynchronized after some predefined out-of-sync detection timeout. The authors present a design space

study which investigates the relationship between the maximum allowed clock drift, the worst-case clock drift rate, the maximum possible diameter of the synchronization spanning tree, and the out-of-sync detection timeout. Their findings on a number of test networks indicate that shorter out-of-sync detection timeouts are needed for higher clock drift rates. The maximum possible diameter of the synchronization spanning tree is negatively affected by higher clock drift rates. Evaluations for a test case regarding schedulability, end-to-end latency, and solving time are conducted. The results show that end-to-end latency increases for higher allowed clock drifts. Maximizing the allowed clock drift yields a maximal robust schedule for a given problem instance, but solving time increases by an order of magnitude compared to setting a fixed maximum clock drift in advance.

Feng et al. [70] consider the scheduling problem in the presence of frame loss. Instead of scheduling redundant streams over disjoint paths, as in [71], [72], and [73], reliability is achieved by multiple transmissions of a stream over the same path. Thus, the proposed approach is only applicable in the case of spontaneous frame loss and temporary link failures. The research work focuses on choosing an appropriate number of repetitions per stream for a trade-off of reliability and network utilization. In contrast to similar works, considerations for AVB and BE streams are also included in the algorithm, as repeated transmissions of TT streams deplete the available bandwidth and may lead to starvation of other traffic otherwise. The presented algorithm uses the SMT model from [29] as a sub-routine. Their results show that increasing the fault probability leads to a higher number of retransmissions which in turn results in less available bandwidth for BE traffic.

In later works, Feng et al. [74] studied a similar problem, but also considered ACK and NACK messages and queue assignment of streams. In contrast to [70], every TT stream is sent exactly twice. Transmission windows for BE streams are computed after the scheduling of TT streams. The scheduled transmission intervals for the retransmissions can be used to transmit BE traffic when no retransmissions are needed.

Dobrin et al. [75] present a heuristic scheme to schedule streams with reliability considerations. They consider transmission losses for frames such that only one frame is affected by a fault at a time and the fault is fixed by some predefined number of retransmissions. Their approach first tightens the deadlines to take some number of retransmissions into account. Then, they schedule streams in earliest deadline first order. Additional considerations for rate constrained traffic are also included in their scheme, following the scheduling of the TT streams. Unfortunately, no evaluations are presented. The authors note that future works will address more realistic fault models.

5) RECONFIGURATION OF SCHEDULES

The reconfiguration of schedules has two distinct meanings in the context of scheduling for the TAS. First, an update to an

existing schedule must be computed when the set of streams or the requirements change. Second, a modified schedule from the first case must be deployed to hardware devices, i.e., GCLs and transmission offsets are reconfigured. This section focuses on the first meaning as the deployment of schedules is out of scope for scheduling algorithms. Adding and removing streams from an existing schedule is necessary in dynamically changing environments, e.g., automotive use cases. While removing a stream is straightforward, adding new streams may require more effort. We summarize research works concerned with this problem extension.

Raagaard et al. [76] propose an algorithm for online scheduling of new TT streams in an existing schedule. They use a heuristic which schedules streams as early as possible such that schedules comply with isolation. When a new stream should be added to an existing schedule, they calculate whether there is a starting offset such that the stream can be scheduled without changing the existing schedule. If this is not possible, the stream is assigned to unused queues of the egress ports along the stream's path. The authors state that adding streams to an empty schedule resembles the worst case of removing all streams from a schedule and adding a set of new streams. Thus, they evaluate how many streams can be scheduled in a specific time. They report that their heuristic is able to schedule about 1300 frames per second in medium-sized test cases.

Pang et al. [77] compute schedules with an ILP such that updating a schedule does not lead to frame loss or additional update overhead. In contrast to [28] and [57], their approach is not limited to TSN and streams are scheduled one by one. Schedules of streams from previous iterations are fixed in later iterations. When some stream cannot be scheduled, backtracking is used by removing some stream of an earlier iteration from the schedule. The authors prove that a set of additional constraints of the ILP imply no conflicts during schedule updates. They evaluate their algorithm with respect to frame loss during updates and update duration on real-world train and automotive networks. The results confirm that no frames are lost and no time overhead is needed for schedule updates.

Another algorithm for schedule updates is proposed by Wang et al. [78]. They present a heuristic scheduling algorithm with backtracking similar to [68]. Additionally, they present an algorithm for incremental schedule updates which omits frame loss during updates. A comparison between both algorithms shows that the incremental update algorithm is faster while it has poor schedulability for higher network utilization.

Gärtner et al. [79] introduce a measure for schedule flexibility denoted as *flexcurve*. The flexcurve is a function that captures the number of possible embeddings of a stream in an existing schedule. Thus, higher values correspond to more possibilities to reschedule a stream. Already scheduled streams may be selected with this measure and shifted to other times to introduce gaps for new streams into a schedule. The paper elaborates on the details of computing and updating

the flexcurves. The authors compare their algorithm to a not specified SMT approach and the algorithm of Santos et al. [59]. In contrast to the SMT approach, solving time of the proposed reconfiguration algorithm is linear for up to 100 streams in the evaluation scenario. The approach of Santos et al. [59] results in schedules with lower flexibility and thus is less suitable for dynamic reconfiguration. A journal extension of this work is presented in [80].

6) GCL SYNTHESIS

Most research works use a post-processing to compute GCLs from transmission offsets. However, this comes with the drawback that GCLs have limited size in bridges and a schedule may not be deployable. We present literature which discusses explicit GCL generation.

Jin et al. [30] present an SMT approach to schedule TSN streams with a fixed number of gate openings. Reducing the number of gate events also reduces the number of guard bands, such that more bandwidth is available for lower-priority traffic. Their modelling assumptions regarding queuing are even more restrictive than frame isolation as only exactly one frame is allowed to be in a queue at any given time. Their approach allows multiple queues for TT traffic per egress port, but assigning streams to queues is not part of the SMT model. This is done before solving the SMT model by a greedy heuristic which aims to balance the workload of all queues of an egress port. As their SMT model cannot be solved in reasonable time, they use an incremental scheme to schedule small groups of streams separately. Subsets of streams are scheduled one after another such that the schedules of previously scheduled subsets are fixed in later iterations. The objective when optimizing a subset is to minimize the maximal number of GCL entries for all egress ports. They also propose a heuristic algorithm which complies with a limited number of GCL entries. Their evaluations show that the heuristic algorithm is an order of magnitude faster than naïve heuristics while reducing the number of GCL entries considerably. Instances with up to 10000 streams were scheduled in reasonable time while the SMT approach has not produced a feasible schedule for an instance with 100 streams within 2 days.

Another incremental SMT scheme which aims to reduce the number of GCL entries is given in [81]. Their approach divides the hyperperiod into slices. Streams and GCLs are scheduled for every slice individually. GCLs are updated and deployed at the beginning of every slice during schedule execution. The authors compare the number of GCL entries needed with schedules computed for an entire hyperperiod. Their results demonstrate that the number of GCL entries can be reduced while keeping end-to-end delays in reasonable bounds. However, it is not a surprise that fewer GCL entries are required when updating the GCLs regularly is allowed, as even a single entry per GCL is sufficient with frequent updates.

A rather simple CP model for scheduling on a single link with only four types of constraints is presented in [82].

However, they propose a post-processing to reduce the number of GCL entries needed in a schedule. For a small test case of only three streams, the authors report a reduction of bandwidth loss due to guard bands by 42.8%.

7) TASK SCHEDULING

Tasks are applications running on end stations. We highlight publications which consider the scheduling of tasks on end stations, additionally to scheduling data streams between these tasks.

In [83], Feng et al. compute schedules for streams and tasks sending or receiving streams simultaneously. The model includes dependencies between streams and tasks, e.g., an application can only be executed when all frames of some stream were received. The authors scheduled instances with 11 streams and more than 100 tasks. As many other works, the authors note the exponential increase of solving times for larger instances.

The authors of [84] present a CP model for scheduling of TT traffic which takes characteristics of control applications into account. Control applications have an execution interval and can only produce output streams for actuators when certain input streams of sensors have arrived. Although the quality of control application execution covers multiple aspects, the only one taken into account is jitter. Queuing is allowed in their model, but is restricted to frame isolation. They compare exact and heuristic search strategies to find solutions to the proposed CP model. For all presented test cases, both search strategies find the optimal solution with zero jitter, but the heuristic approach is orders of magnitude faster.

These preliminary works were extended in [85]. In contrast to [84], a more realistic quality measure for streams of control applications is integrated into the CP model. It constitutes of jitter and end-to-end delays of input and output streams of control applications, and jitter for control application execution. They compare their model with the model from [29] which is extended to include stream precedence for input and output streams of control applications. That means the model is able to enforce that control applications are executed after their respective input streams have arrived. Analogously, streams sent by a control application are scheduled to be transmitted after the execution of the application has finished. The authors report that the presented model outperforms the model from [29] with respect to the proposed quality measure by up to a factor of two on the test cases under consideration. Additionally, they compute a schedule for a realistic test case of an automotive mobile robot and validate their algorithm on a simulation platform and on real hardware. The PhD thesis of Barzegaran [86] features this work.

McLean et al. [87] present a converged approach for task and message scheduling in automotive environments using TSN. The authors propose metaheuristics based on genetic algorithms and simulated annealing to compute the mapping of tasks to processing cores. A combination of list scheduling

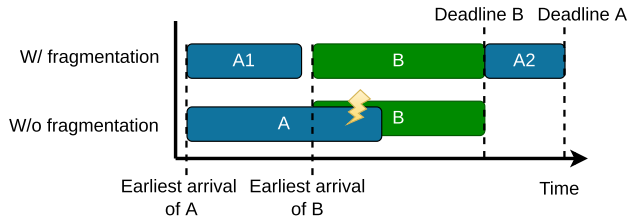


FIGURE 14. Transmissions of two frames A and B over a link to a listener. B cannot be scheduled to be transmitted at another time. In this case, scheduling is only possible when the scheduler splits A into two frames.

and earliest deadline first scheduling is used to compute schedules for message transmissions and task executions. Instead of rejecting solutions violating one or more timing constraints, the objective penalizes such solutions. Thus, the algorithm is able to move towards feasible solutions when finding an initial feasible solution is hard. The evaluations show that the simulated annealing algorithm results in lower solving times and better solutions compared to the genetic algorithm heuristic.

Another converged approach for task and message scheduling is proposed by Arestova et al. [88]. The authors introduce the concept of earliest and latest start times for tasks in cause-effect chains of tasks and streams. These times represent the range of valid execution times for tasks and are used for the fast rejection of invalid solutions. An incremental scheduling heuristic which uses these times is presented. Additionally, a repair function is integrated to recover from cases where timing constraints are violated. The evaluations demonstrate that the approach results in significantly reduced solving times and worst case response times compared to approaches from the related work.

8) OTHER TOPICS

This section summarizes research works with unique topics that fit not well into the previous groups.

Jin et al. propose an SMT model which also handles an optimized fragmentation of messages in [89]. Messages can be transmitted with multiple frames. How messages are split into frames is an additional degree of freedom in the presented optimization. Due to performance reasons when solving the model, they also give heuristics for message fragmentation and scheduling. The presented evaluations demonstrate that schedulability increases considerably by up to 50% when message fragmentation is also taken into account. Figure 14 depicts an example of how schedulability can benefit from message fragmentation. Additionally, the presented heuristic algorithms can schedule instances an order of magnitude larger than the SMT approach.

A genetic algorithm approach which takes frame preemption into account is presented in [90]. Their model contains different kinds of MAC interfaces for preemptable and non-preemptable frames. Consequently, the presented synthesis problem not only covers the assignment of streams to queues, but also the assignment of queues to interfaces. Queues are

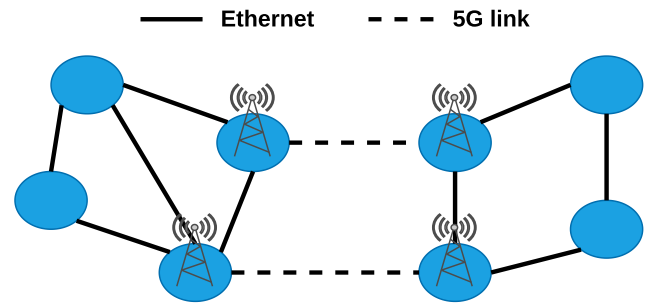


FIGURE 15. Example of a converged network with 5G and Ethernet links as considered in [91].

strictly prioritized, i.e., frames contained in a higher-priority queue always preempt frames of a lower-priority queue. The proposed GA aims to maximize the reliability of a schedule. Reliability of a stream is defined as the maximum number of allowed retransmissions without missing the deadline, and the reliability of a schedule is the minimum reliability of all streams. The authors present a comparison of the proposed GA with well-known approaches from automotive traffic scheduling. The baseline approaches are outperformed with respect to schedulability and reliability. The authors explain this result with the fact that their algorithm is specifically constructed to use all the available TSN queues and to utilize them in a way suitable for preemption.

The authors of [91] give a CP model for TSN in joint converged wired and wireless networks. Their model integrates Ethernet and 5G links simultaneously. Figure 15 depicts an example for such a converged network. Frames transmitted over a 5G link must be scheduled to fit into predefined transmission slots. They aim to minimize unusable resources in both types of links, i.e., time occupied by guard bands for Ethernet links and unused bandwidth resources for 5G links. The presented evaluations indicate that minimizing only one kind of unusable resources leads to unsatisfying results for the respective other kind.

Lin et al. [92] evaluate the impact of the so-called *network cycle* to schedulability. The network cycle is a design methodology for frame schedules. All stream periods are assumed to be integer multiples of the network cycle. Frame transmissions are aligned with network cycles. The rationale of this is to omit conflicts between streams with different periods when streams are scheduled incrementally. They propose an incremental heuristic which considers the network cycle. The authors report the highest schedulability when the network cycle is set to the greatest common divisor of all stream periods.

The authors of [93] developed a graphical modelling tool for TSN scheduling. They use logic programming to deduce facts about the given problem instance. These facts are in turn used for constraint generation of an SMT model. If an instance is infeasible, the conflict refinement capabilities of the SMT solver is leveraged to guide the user in changing the network configuration appropriately. Three test scenarios

are presented where the streams causing infeasibility are identified.

Machine learning techniques were introduced to the domain of TSN scheduling in [94]. Tu et al. present a semi-supervised machine learning model to partition streams in groups before scheduling. They compare their approach with the partitionings in [71] and [95], and state that they are outperformed regarding schedulability. However, it is not clear how this statement is backed by the actual computation of schedules with the resulting stream groups.

We highlighted the contributions of research works for the scheduling problem with fixed routings. We compare and discuss the research works presented in this section together with the research works for the joint routing problem in Section V.

B. SCHEDULING W/JOINT ROUTING

In this section, we give an overview of research work which inspects the joint routing and scheduling problem. In contrast to works in IV-A, algorithms proposed by publications in this section compute a routing and a schedule for a given set of streams simultaneously. Again, we group the literature based on the main topic of the respective papers.

1) JOINT SCHEDULING AND ROUTING W/O PROBLEM EXTENSIONS

This section compiles publications which handle the joint routing and scheduling problem. Research works are only included when they do not focus on an additional topic highlighted in this survey.

An early ILP model which addresses the problem of joint routing and scheduling is presented in [8]. Although it is not exclusively for TSN, the authors state it is applicable for such networks. Their evaluations show that schedulability increases considerably compared to the same test cases with a fixed routing. They compare the solving time of their ILP for joint routing and scheduling with ILPs solely for scheduling. As expected, the solving time is larger for joint routing and scheduling compared to scheduling with a fixed routing. Nevertheless, they still recommend joint routing as solution quality increases considerably.

Falk et al. [96] extend the ILP from [28] to simultaneously compute routing and schedule of TT streams. They analyze the scalability of the joint routing and scheduling problem using ILPs. The authors report that solving time is more influenced by the number of streams than the size of the network topology for their ILP. The evaluations show that network topologies with more paths between any pair of nodes tend to yield harder problem instances, as more routings are possible for any stream.

Nie et al. [97] schedule and route streams incrementally. Streams are grouped by divisibility of their periods, such that streams in the same group can share the same links. The authors focus completely on the case of large period

differences and omit the worst case of all streams having the same period. In contrast to similar works, e.g., [71] and [98], they consider only no-wait scheduling. Time is divided into time slots whose lengths equal the greatest common divisor of the periods of all streams. Although many evaluations are performed for different network topologies, network sizes, and traffic types, no results not seen in other works were presented.

Xu et al. [99] propose an incremental SMT scheme similar to [71] and [98]. However, they partition streams with machine learning using some of the ideas from [94]. The authors compare this partitioning approach with the partitioning algorithms from [71], [94], [95], and [100]. The best schedulability was obtained for the proposed partitioning method, second to the methods from [71] and [94]. Schedulability is slightly increased when more streams are scheduled simultaneously, as more conflicting streams are handled in the same iteration. Additionally, the authors compare the incremental scheme with their global scheduling approach from [101]. The incremental scheme outperforms the global approach with respect to schedulability and scalability. The difference in schedulability between both methods increases for higher link utilization.

The authors of [102] present a PBO model for joint routing and scheduling. They compare the solving time of their PB approach with the solving time when routing and scheduling are computed in separate steps by the same model. Their initial evaluations indicate that solving routing and scheduling in separate steps reduces the overall solving time. Surprisingly, their evaluations also show that the 2-step approach performs significantly worse for larger instances compared to the joint approach. They explain this behavior by the capability of SAT solvers to learn from conflicts. Whenever the solver runs into a conflicting variable assignment, it interferes the cause of the conflict and adds a clause to the model which prevents the conflict explicitly. The learned clauses are dropped after the routing step in the 2-step approach. Schedulability increases when routing and scheduling are performed in a single step. They state that instances with more routing options lead to easier solvable scheduling problems as streams can be distributed over the network.

Arestova et al. [103] construct a genetic algorithm for joint routing and scheduling. In contrast to other works with genetic algorithms [100], [104], the authors focus on elaborating on the construction for such an approach in detail. They combine the genetic algorithm with a neighborhood search heuristic to find better solutions efficiently. They allow queuing with flow isolation constraints from [29]. Additionally, a schedule compression algorithm similar to the one in [28] is presented, which is used to reduce the number of guard bands. In a brief evaluation section, they compare their approach with the well-known NEH algorithm [105] from job-shop scheduling. The proposed approach finds feasible schedules faster, while the resulting schedules have comparable flowspans. The authors report that scheduling with joint

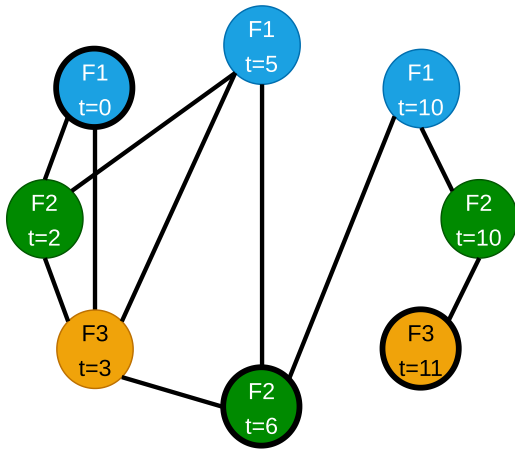


FIGURE 16. Example of a conflict graph used in [108] for a single link topology. Assume the transmission of each frame takes 5 time units. Edges indicate stream schedules which are not compatible. The black circled vertices are an independent set and induce a schedule.

routing takes only slightly more time than scheduling with fixed routing with the genetic algorithm.

Kentis et al. [106] investigate the relation of port utilization and GCL schedule duration in a short paper. They employ a simple heuristic for scheduling which is not further explained, and compare the resulting schedule duration with shortest-path routing and the proposed congestion-aware routing. For most test cases, the duration of the schedule is reduced. However, they do not motivate why shorter schedule durations are beneficial.

The authors of [107] present an algorithm based on ant colony optimization. First, they give a heuristic based on simulated annealing and genetic algorithms. The authors state that integrating transmission delays into this approach is hard and propose an ant colony optimization heuristic to overcome this problem. They give the fundamental building blocks of such an algorithm and demonstrate that it can be suitable for TSN scheduling, but also note that further investigation is needed. Unfortunately, they do not elaborate on the routing, and the only related evaluation indicates that increasing the number of edges increases the solving time. The authors compare their TSN-adapted ant colony optimization algorithm with another ant colony optimization that is not specific for TSN scheduling. They conclude that the adapted algorithms results in less jitter and end-to-end delays, and converges after fewer iterations.

Falk et al. propose a joint routing and scheduling algorithm in [108] which is not based on constraints for frame transmissions. Their approach constructs a conflict graph where each vertex represents a schedule for a single stream. Vertices are connected by an edge if and only if the corresponding stream schedules are conflicting. This reduces the scheduling problem to finding an independent set in a conflict graph, i.e., a set of vertices which are pairwise not connected by an edge. Figure 16 depicts an example for a conflict graph and an independent set. The authors use incremental heuristics to

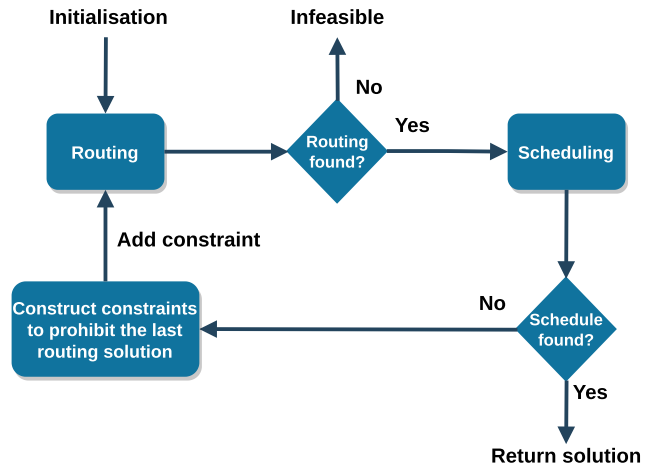


FIGURE 17. Flow diagram of the proposed approach in [109].

construct independent sets in such graphs. Their evaluations demonstrate that the conflict graph approach has advantages regarding runtime and memory consumption compared to ILPs. They remark that their implementation is just a proof of concept, and more efficient algorithms to find independent sets are known. They further note that this approach is cheap, as no expensive ILP solver is needed.

An enhanced CP approach for routing and scheduling is presented by Vlk et al. [109]. The authors present separate models for routing and scheduling, and use them in a problem decomposition algorithm. First, they compute a routing for the given streams. A schedule is computed using this routing. If no schedule was found, constraints are added to the routing model to prohibit the last routing solution. These steps are repeated until a schedule is found. Alternatively, it may be the case that all possible routings for some stream lead to a conflict while scheduling. In that case, an instance is deemed as infeasible. Figure 17 depicts a flow diagram of the proposed approach. Most other research works which performs routing and scheduling in separate steps considers an instance infeasible after only one pass of routing and scheduling. The model also includes queue assignment of streams as additional degrees of freedom. The authors substitute their scheduling model with the algorithms from [28], [29], and [110], and compared schedulability of the resulting algorithms with their approach. Their CP model was able to schedule the most instances, while the SMT model scheduled significantly fewer instances than all other algorithms. Scheduling time was similar for all algorithms except for the SMT model, which needed multiple times longer for most instances.

He et al. [111] present a deep learning based approach for joint routing and scheduling. They use a graph neural network to handle arbitrary sized network topologies. They evaluate their approach on various random network topologies and compare it with [8], [28], [40], and [104]. All other approaches were outperformed in regard to schedulability and scalability for various numbers of streams and network

topology sizes. They also compare different encodings, policies, and sampling strategies featured in their deep learning approach. The results give useful insights for future works involving deep learning in TSN scheduling. Additionally, the authors present measurements of jitter on a real hardware testbed which integrates their deep learning scheduling algorithm. They report no frame losses and ultra low jitter, which indicates that the constructed schedules are valid.

2) SCHEDULING W/RELIABILITY

Reliability is an important topic in the literature of joint routing and scheduling. The possibility of selecting disjoint paths for redundant stream copies further increases reliability in these research works.

Pozo et al. [112] present an ILP for joint routing which considers reliability constraints. After a single link failure, all streams over this link must be rescheduled and rerouted. The authors propose a fast heuristic for this case. They also evaluate which properties of a schedule are beneficial for the reparability in case of a failure. The results indicate that schedules which maximize the gaps between frame transmissions are much easier to repair than schedules which minimize the flowspan, even for three simultaneous link failures.

Atallah et al. [113] give a heuristic for fault-tolerant joint scheduling, routing, and topology generation. Their algorithm starts with a full mesh topology. Streams are routed and scheduled one after another. A k -shortest-paths algorithm is used to enumerate possible paths for a stream. If a path with available time slots is found, schedule and routing are fixed for later iterations. This is repeated multiple times with disjoint paths for redundant copies of a stream to ensure reliability. Links and bridges are only included in the final topology when they are used by some stream. The algorithm also selects bridges such that more expensive bridges are only used when necessary. Figure 18 depicts this approach for topology generation. The authors compare their algorithm to another approach which realizes redundant paths through multiple copies of the network topology. The proposed algorithm scheduled all problem instances, while it reduces financial costs for network hardware considerably.

The authors of [71] propose an incremental ILP scheme to comply with requirements for the robustness against single link failures. First, the authors present a GRASP heuristic for routing which considers reliability constraints. Streams are replicated and routed over disjoint paths to comply with requirements regarding robustness to single link failures. The resulting routing is used as input to the incremental ILP approach. Streams are partitioned into groups by introducing a conflict metric and computing a weighted cut in the conflict graph. Groups of streams are scheduled one after another. The computed schedules are fixed when the next group is scheduled. They model egress ports with only one queue for TT traffic and frame isolation. A comparison of the presented ILP with the ILPs from [8] and [102] demonstrates that it outperforms both approaches regarding solving times.

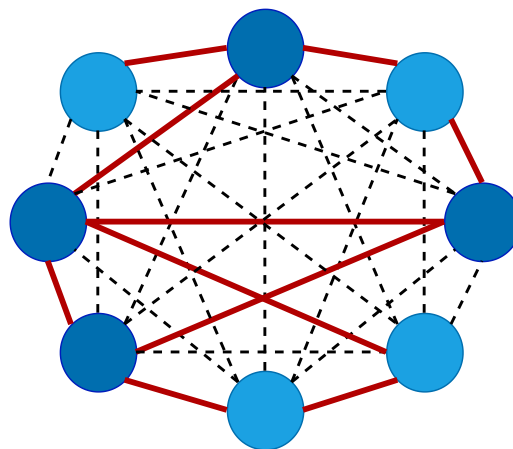


FIGURE 18. Topology generation approach of [113]. A full mesh topology is used during routing and scheduling. Links used in the final routing are indicated in red. Only these links are included in the final topology. The approach covers the selection of bridges from a library depending on the generated topology. More expensive bridges with a higher number of ports are indicated in dark blue.

Instead of robustness against link failures, Zhou et al. [114] consider reliability against frame loss, i.e., frames that are lost spontaneously during transmission without a permanent link failure. They integrate constraints regarding the loss probability along the routed path of a stream in their SMT model. However, these probabilities are only approximated, as the used theory solver cannot handle exponentials. An incremental scheme similar to [71] is used. Subsets of streams are scheduled and routed one after another until all streams are scheduled. Stream schedules are fixed in subsequent iterations. They use redundant copies of streams to further reduce the probability of frame loss, as there may be no single path with the required reliability. In contrast to other works, e.g., [71], [72], and [73], they do not enforce paths to be link disjoint. Their evaluations show that schedulability with a given level of reliability against frame loss increases with a higher number of redundant copies per stream.

Syed et al. [115] present an ILP and a heuristic for scheduling and path selection in in-vehicle networks. They leverage Frame Replication and Elimination for Reliability (FRER) [17] to ensure robustness against frame loss of safety-critical streams. The ILP model is similar to the ILP used in prior works by the same authors [116]. They report solving times of about a day with the ILP while the heuristic solved the same instances in a few minutes.

Following their works in [115], Syed et al. [117] developed an alternative to FRER. The authors propose a network coding scheme to mitigate temporary and permanent link failures. Two disjoint paths are used to transmit two frames. A third path disjoint from the other two is used to transmit the XORed data of these two frames. The loss of one frame can be tolerated as the lost frame can be reconstructed from the other two. Therefore, the redundant transmission of n frames results in $\frac{3}{2n}$ frame transmission with this scheme. This is a

significant reduction compared to the $2n$ frames needed with FRER.

Another incremental scheme for scheduling and routing in safety-critical automotive applications is presented by Zhou et al. [118]. They consider possibly undetected systematic faults of bridges, i.e., implementation bugs or divergence from specifications, instead of randomly arising errors like frame loss. Messages and bridges have an Automotive Safety Integrity Level (ASIL) assigned [119] which defines reliability constraints of the respective component. A higher ASIL corresponds to higher reliability. Additionally, to computing routing and scheduling, their algorithm also selects which bridges to use from a library. Messages can be decomposed into redundant message copies with lower ASIL to be sent over bridges with lower ASIL. A comparison of the presented algorithm with and without message decomposition shows that the total financial costs for bridges can be reduced by up to 23.55% in the evaluation scenarios. The authors note that higher ASILs increase the required number of message copies, which leads to more congestion in the network and thus higher end-to-end delays. Evaluations on a real-life automotive test case are presented. Synthesis time increases considerably with ASIL decomposition. However, the selected bridges cost only a third compared to using only bridges with the highest ASIL. The PhD thesis of Zhou [120] compiles the content of [114], [118], and [121].

The authors of [72] present separate CP models to compute schedules and routings as work-in-progress. These models take security and reliability considerations into account. The routing computed with the first model is used as fixed input for the scheduling model, similar to [71]. Redundant streams with disjoint paths are added if needed to comply with security and reliability constraints.

The ideas from [72] are extended in [55]. Besides the CP model, a simulated annealing algorithm combined with a list scheduler is given. Additionally, a post-processing for latency reduction of scheduled streams is applied after scheduling. Their evaluations without security and reliability constraints indicate that the SA approach is able to find a feasible schedule in reasonable time, even for huge problem instances. However, they also introduce a measure for schedule and routing costs. This measure contains stream latencies, penalties for streams which were not scheduled, and penalties for overlapping paths. The results demonstrate that schedules computed by SA have up to three times higher costs compared to schedules computed by the CP approach. Introducing the security and reliability constraints to the same problem instances increased the costs of schedules computed by SA by up to a factor of ~ 3.5 . Nevertheless, the authors state that the SA approach can be useful in comparing costs and reliability capabilities of topologies, or to reconfigure the network in case of link failures.

Li et al. [122] propose a heuristic for joint routing and scheduling with reliability constraints. A greedy algorithm is used to select paths for redundant copies of streams such

that link utilization is balanced. Frames are scheduled as soon as possible. Both algorithms are combined in an iterative local search scheme. Already scheduled and routed streams are randomly removed from time to time, and the remaining streams are rescheduled and rerouted in random order. While the authors report a reduction in frame losses by their approach, end-to-end delays are significantly larger compared to schedules with routings computed by Dijkstra's algorithm.

3) SCHEDULING W/OTHER TRAFFIC

This section presents research works concerned with scheduling in the presence of other traffic classes.

Gavriluț et al. [123] construct a GRASP heuristic to schedule TT streams while taking AVB traffic into account. In contrast to [57], their approach handles TT and AVB streams simultaneously. The routing of AVB streams is given and cannot be changed. The problem of finding a routing for AVB streams in the presence of TT streams was addressed and evaluated by Laursen et al. [124]. The authors of [124] propose a hill climbing based heuristic algorithm. In the first evaluation of [123], the authors use a shortest paths algorithm to compute the routing for TT streams. The results show that using the GRASP heuristic with an objective that considers tardiness of AVB streams leads to AVB streams meeting their deadlines. In contrast to that, the GRASP heuristic with other objectives not considering AVB streams results in schedules with late AVB streams. Even better results are obtained when a routing with load balancing is used before scheduling, which also decreases overall runtime. They report that AVB traffic does not benefit from minimizing the number of queues for TT streams. However, this is rather obvious, as their system model assumes that AVB streams already have an assignment to AVB queues. Solving time of the GRASP heuristic increases considerably when AVB streams are taken into account. A short preview of these results was previously published in [125] and the implementation details of the heuristic are elaborated in [126].

The routing algorithm in [124] only considers AVB streams in an offline scenario. Another work which focuses on the routing of AVB streams in the presence of scheduled traffic is presented in [127]. The authors propose an online routing algorithm for AVB and TSN streams. The algorithm is based on ant colony optimization and compared to the approach of [124]. The evaluations indicate that the ant colony optimization algorithm outperforms the approach of [124] with respect to solving times.

Gavriluț et al. [128] propose an algorithm which assigns messages to traffic classes, i.e., whether a message should be transmitted with TT or AVB streams and which AVB class should be used. The assignment algorithm is based on the tabu search metaheuristic. Additionally, the parameters for the CBS are estimated such that AVB streams comply with their real-time requirements. Afterwards, streams are scheduled

with an adaption of the algorithm from [123] and [126]. The evaluations show that the assignment algorithm significantly increases the number of schedulable streams. Compared to the SMT approach of [29], the assignment to traffic classes increases the schedulability of legacy streams that cannot be reassigned or rescheduled.

Berisa et al. [129] propose a heuristic for the joint routing and scheduling of TT streams in the presence of AVB streams. They make use of frame preemption to increase the schedulability of AVB streams. To that end, they present a worst-case response-time analysis of AVB streams with preemption. The heuristic is based on prior works by Gavriluț et al. [123]. Their evaluations demonstrate that the schedulability of AVB streams can be increased by allowing frame preemption while the runtime of the heuristic also increases significantly in this case.

Alnajin et al. [32] give a QoS-aware routing algorithm for TSN streams with respect to various metrics. They present four scheduling heuristics combined with these routings. They compare these algorithms regarding the number of guard bands needed in the resulting schedules. Their evaluations show that their heuristics can reduce the number of guard bands significantly. They note that reducing the number of guard bands is beneficial for BE traffic.

Li et al. [130] present a heuristic for joint routing and scheduling to eliminate non-deterministic queuing delay in networks with mixed time-critical traffic. Their scheduling algorithm divides the bandwidth resources into time slots and assigns streams to these slots such that transmission conflicts cannot arise. Similar to [31], the maximum length of the resulting GCLs is bounded instead of being computed by a post-processing from transmission offsets. The solving time with the heuristic is compared to [71], [96], and [103]. Solving time is the only inspected metric as the presented algorithm, and the three compared approaches have no objective functions. In the presented scenarios, all three methods were outperformed by multiple orders of magnitude. The authors report schedules for 4000 streams with just 12 GCL entries per egress port on average.

Yang et al. [131] use deep reinforcement learning for the joint routing and scheduling problem. Additionally, they take AVB and BE streams into account. The authors elaborate on the details of their machine learning model and present evaluations about the learning phase. They introduce three baseline approaches also based on machine learning for comparison. The proposed model results in slightly lower average latencies for all traffic classes in the evaluation scenario.

4) MULTICAST

This section highlights research works specifically concerned with multicast streams in a joint routing and scheduling approach.

The joint routing and scheduling model from [8] is extended for multicast support in [132]. The authors state that while this extension is trivial for pure scheduling models,

joint routing and scheduling with multicast is more complicated as additional constraints for the routing are needed. Various pre-processing steps are presented to reduce the solution space and thus solving time. The authors report that the time to find a feasible solution was reduced by up to 82.4% while the overall solving time was reduced by up to 47.6%.

Another approach for joint routing and scheduling with multicast streams is presented by Li et al. [133]. Similar to [132], the authors use pre-processing to simplify solving of the model. The streams are divided into groups by spectral clustering based on their properties. Similar to [71] and [72], these groups are routed and scheduled one after another such that previously computed schedules and routes are fixed. The authors report that random clustering result in slightly longer flowspans. As in similar incremental approaches, reduced overall solving times and increased schedulability are reported.

Yu et al. [134] propose an incremental approach with ILPs. In contrast to [132], they route and schedule multicast streams one by one. Multiple queues per egress port and queue assignment are also integrated in their model. Additionally, they propose a pre-processing scheme which aims to simplify the topology. The pre-processing merges cliques in the topology to a single link. If routing and schedule can be computed, both are modified for the original graph. Otherwise the conflicting links are expanded and routing and scheduling are repeated. Compared to [7] with a Steiner tree as fixed routing, the proposed approach can schedule significantly more instances.

A biology-inspired algorithm is given by Pahlevan et al. [104]. They construct a genetic algorithm for joint routing and scheduling which also comprises features like multicast streams and dependencies between streams. The authors state multicast capabilities as one of their main contributions, but consider multicast streams simply as multiple unicast streams. In contrast to [29], [31], and [125], only a single queue per egress port is dedicated to TT traffic. While their evaluations indicate that solving time increases compared to scheduling with a fixed routing, they show that schedulability increases by joint routing and scheduling.

In later works, Pahlevan et al. [100] present a heuristic list scheduling algorithm for the same purpose. They model queuing and multicast streams in the same way as in [104]. Their evaluations again demonstrate that joint routing and scheduling increases schedulability.

5) RECONFIGURATION OF SCHEDULES

Reconfiguration of streams can benefit from modifying not only a schedule, but also the respective routing. Newly added streams can be routed over paths with low utilization. This section compiles the literature about reconfiguration in joint routing and scheduling approaches.

Research work from Syed et al. [116] deals with joint routing and scheduling in in-vehicle networks. They propose an ILP model for streams that are known in advance which takes load balancing into account. They compute schedules

and routings for these streams such that as many streams as possible can later be added dynamically. The evaluations compare algorithmic details that are hard to assess without detailed knowledge of the presented approach.

Following their work in [116], Syed et al. present multiple heuristics for the dynamic scheduling of new streams in an existing schedule [135]. Their heuristics are based on modelling the scheduling problem as a vector bin packing problem. They evaluate the time needed for adding new streams in an automotive use case, as reconfiguration in such scenarios has strict timing requirements.

The authors of [33] construct multiple heuristics for dynamic scheduling and routing with reliability constraints. All heuristics are based on the same idea as in [135]. Every stream is replicated twice when added to an existing schedule to ensure reliability. The best heuristic is able to schedule 500 streams in about 410 ms. The authors state this is a reasonable response time in automotive use cases.

Yu et al. [136] developed a heuristic for online rescheduling in scenarios with virtual machines as communication endpoints. Virtual machines in a cloud computing environment may be migrated from one physical device to another such that schedules and routings must be updated. Additionally, all streams are multicast streams, which complicates rescheduling after a VM migration. Therefore, the multicast tree for a stream is computed such that the maximal distance from any possible device where a VM could run to any destination is minimized. The authors state that this will reduce conflicts when a VM is migrated, as the new paths are short. Given a schedule and a stream that is migrated, a greedy heuristic computes the new schedule based on the precomputed multicast tree. The authors compare their proposed routing heuristic with an optimal routing obtained by an ILP. Solving times are significantly reduced, while the routing objective grows only slightly compared to the optimal routing. Schedulability in case of a migration is considerably increased in comparison to the same scheduling heuristic used with a routing computed by the KMB algorithm [137].

Li et al. [138] consider the reconfiguration of routing, scheduling, and mapping of applications to end stations in case of permanent end station failure. They extend the ILP of [139] to schedule applications to end stations for global reconfiguration. As the resulting ILP instances are hard to solve, they propose a heuristic routing and mapping algorithm as alternative. The results of this heuristic are fixed in the ILP model, such that only a schedule is computed. The heuristic approach is able to reconfigure almost all instances, while the ILP times out for most of them in their evaluations. While both algorithms have exponential runtime in the number of streams, the heuristic is two orders of magnitude faster for the considered instances.

An incremental approach which schedules streams one by one is presented in [98]. In contrast to [134], the computed schedules are constrained to no-wait scheduling, i.e., no queuing delays are allowed. The authors compare the proposed

approach with [8] and [71] with respect to schedulability and show that schedulability is slightly increased. The proposed pre-processing for the routing approach gives only minor improvements regarding schedulability. The authors report that 97.5% of the streams in an instance with 2000 streams were scheduled in less than 10 seconds per stream. They state this is fast enough for online scenarios.

6) OTHER TOPICS

This section summarizes research works with unique topics that do not fit well into the previous groups.

The authors of [121] propose a heuristic model to schedule streams in the presence of frame preemption similar to [90]. Additionally, they also include route computation in their algorithm. They present an SMT model for this purpose and use it in an incremental approach, similar to [95], [102], and [140]. The presented results show that scheduling time not only increases with the network size and the number of streams, but also with the maximum number of allowed preemptions and retransmissions. However, allowing more preemptions increases schedulability only to some instance-specific threshold.

Gavriluț et al. [73] give multiple algorithms to simultaneously compute scheduling and routing of TT streams. In contrast to [71], [72], and [96], these algorithms additionally generate the network topology with minimal financial costs imposed by network hardware. They present a problem-specific heuristic, a GRASP heuristic, and a CP approach, and compare them to each other regarding solving time and solution quality. Their optimization objective captures worst-case end-to-end delays as well as topology costs, i.e., costs for links and bridges which are selected from a library. Redundant copies of streams are included for reliability considerations. Their evaluations focus on a comparison of the three presented algorithms. As expected, the CP approach does not scale well. The GRASP heuristic finds better solutions in minutes compared to the CP approach in two days.

An SMT model which includes scheduling, routing, and queue assignment of streams simultaneously is presented by [101]. The authors state that saving bandwidth by not using the same GCL cycle for all egress ports is also novel to their approach. However, this is not true as other works even schedule GCL closing events, e.g. [30] and [41]. They propose to minimize the number of bridges used by scheduled traffic in order to maximize utilization. In comparison to the list scheduler of [100], schedulability is increased while the solving time approaches the timeout after 40 h for fairly small instances.

Zhang et al. [141] construct a heuristic which allows different routes for frames of the same stream to enable load balancing. The required mechanism is implemented by an SDN architecture. The scheduling procedure is a mix of evolutionary algorithm and greedy algorithm. Multiple variations of the heuristic are compared in the evaluations. In the

presented scenarios, scheduling time increased linearly with the number of streams.

Another incremental scheme for scheduling and routing is presented by Mahfouzi et al. [95], [140]. The authors investigate the stability of control applications, i.e., latency and jitter of messages sent by these applications. Instead of grouping streams by some conflict measure, they divide the network period in slices and group the streams by the time slice in which their transmission can start. They allow routing only over some fixed number of precomputed shortest paths per source-destination pair, similar to [123] and the AVB routing in [57]. Their model allows unrestricted queuing without further discussion of this topic. The evaluations indicate that the number of allowed paths has a huge impact to solving time. More possible paths result in a significant increase in solving times. However, they note that three paths per pair of nodes may be sufficient, as schedulability is over 90% in this case. They conclude that the search space can be reduced without decreasing schedulability considerably.

Yang et al. [142] present a network architecture for industrial use cases based on TSN hardware and software-defined networking (SDN). They focus on so-called chain flows. Chain flows consist of multiple stream which are joined at one or more nodes. For instance, an industrial controller may join streams from multiple sensors and forward a single stream to an actuator. The authors propose a tabu search heuristic and an ILP for the scheduling of chain flows. They report benefits in scalability and schedulability in comparison to handling every stream of a chain flow individually.

Chain flows are further investigated by Gong et al. [143]. They propose a heuristic time-tabling algorithm combined with a tabu search for schedule reconfiguration when the network topology is changed. In contrast to the magazine article [142], they elaborate on the details of these algorithms. However, the reported results are consistent with the results in [142].

Hellmanns et al. [144] focus their work not on the ability to compute schedules, but analyze how input pre-processings and solver configuration influence the scalability of solving a joint routing and scheduling ILP model. They categorize optimizations by whether they are input pre-processing, e.g., topology reduction, model generation related, e.g., tighter variable bounds, or solver configurations, e.g. the use of value hints for variables. They give an ILP without any optimizations as baseline for their evaluations. Different combinations of the proposed optimizations are tested on the same set of problem instances and compared with respect to scalability and schedulability. Their evaluations indicate that solving time can greatly benefit from input pre-processings, but the effects of model generation optimizations and solver configurations are negligible. Some of the optimizations even increase solving time. However, queuing is not supported by their base model. Thus, the observations only hold for the no-wait case without queuing delay. It is not clear whether these

results can be transferred to other problem extensions from the literature.

Bhattacharjee et al. [145] propose two algorithms for the placement of talker applications in a network. Additionally, both approaches also solve the joint routing and scheduling problem. The first algorithm is an ILP for the placement of talker applications that is combined with the GRASP heuristic of [123]. The second algorithm is a simulated annealing (SA) heuristic which computes the placement of talker applications, the schedule, and the routing for a given problem instance. The evaluations show that both algorithms behave approximately similar with respect to load balancing and solving times. However, the authors report considerably reduces stream latencies with the SA heuristic.

V. COMPARISON AND DISCUSSION

We compare the presented research work from Section IV. First, we compile modelling assumptions and problem extensions. Second, we present common scheduling objectives. Then, we investigate problem instances used for evaluations. Finally, we summarize results regarding the scalability of the presented approaches.

A. MODELLING ASSUMPTIONS AND PROBLEM EXTENSIONS

Table 2 compiles important modelling assumptions and problem extensions in the surveyed research works with fixed routings. Table 3 shows the same information for research works about the joint routing problem. In the following section, we compile the contributions to each of these topics.

1) OTHER TRAFFIC

Only five works examine TT and AVB streams simultaneously. Pop et al. [57] present a GRASP heuristic for the handling of AVB streams. The heuristic gets a schedule of TT streams as input and cannot change it. The authors of [125] present a short preview of AVB-aware scheduling, which was later extended in [123]. An adaption of this approach was used in [128]. The authors present an algorithm to assign messages to traffic classes in networks supporting AVB and TSN simultaneously. Feng et al. [83] consider the bandwidth available to AVB and BE traffic in their approach as they consider repeated frame loss which may result in starvation. Berisa et al. [129] use frame preemption and a worst-case end-to-end delay analysis to increase the schedulability of AVB streams. Huang et al. [68] give parameters for AVB streams in an in-vehicle network and include them in their evaluation scenario. Wang et al. [67] consider the joint handling of AVB and TT streams. AVB streams are shaped by CQF. Their objective aims to reduce the influence of non-periodic BE traffic to AVB streams. Some works focus solely on the routing of AVB streams in the presence of scheduled traffic in TSN [124], [127]. Li et al. [58] present a heuristic to configure the CBS in the presence of scheduled traffic.

TABLE 2. Overview of considered problem extensions and restrictions in the literature of scheduling approaches with a fixed routing.

Research work	AVB	BE	Queuing	Fixed GCL length	Reconfiguration	Reliability	Multicast	Task scheduling
Ansah <i>et al.</i> [45]	-	-	✓	-	-	-	-	-
Arestova <i>et al.</i> [88]	-	-	✓	-	-	-	-	✓
Barzegaran <i>et al.</i> [85]	-	-	(✓)	-	-	-	✓	✓
Barzegaran <i>et al.</i> [64]	-	(✓)	✓	✓	-	-	-	-
Barzegaran <i>et al.</i> [84]	-	-	(✓)	-	-	-	-	✓
Bujosa <i>et al.</i> [54]	-	-	✓	-	-	-	✓	-
Chaine <i>et al.</i> [53]	-	-	(✓)	-	-	-	-	-
Craciunas <i>et al.</i> [29]	-	-	(✓)	-	-	-	-	-
Craciunas <i>et al.</i> [69]	-	-	(✓)	-	-	✓	-	-
Dai <i>et al.</i> [82]	-	(✓)	-	-	-	-	-	-
Dobrin <i>et al.</i> [75]	-	-	✓	-	-	✓	-	-
Duerr <i>et al.</i> [28]	-	✓	-	-	-	-	-	-
Farzaneh <i>et al.</i> [93]	-	-	-	-	-	-	-	-
Feng <i>et al.</i> [70]	✓	✓	(✓)	-	-	✓	-	-
Feng <i>et al.</i> [74]	-	✓	✓	-	-	✓	-	-
Feng <i>et al.</i> [83]	-	-	(✓)	-	-	-	✓	✓
Gärtner <i>et al.</i> [79][80]	-	-	(✓)	-	✓	-	-	-
Gavriliuț <i>et al.</i> [125]	✓	-	(✓)	-	-	-	-	-
Gavriliuț <i>et al.</i> [128]	✓	✓	(✓)	-	-	-	✓	-
Ginthör <i>et al.</i> [91]	-	✓	✓	✓	-	-	-	-
Hellmanns <i>et al.</i> [40]	-	(✓)	(✓)	-	-	-	-	-
Houtan <i>et al.</i> [62]	-	✓	(✓)	-	-	-	-	-
Huang <i>et al.</i> [68]	✓	(✓)	(✓)	-	-	✓	-	-
Jin <i>et al.</i> [89]	-	-	-	-	-	-	-	-
Jin <i>et al.</i> [30]	-	(✓)	(✓)	✓	-	-	-	-
Kim <i>et al.</i> [42]	-	(✓)	✓	-	-	-	-	-
Kim <i>et al.</i> [43][44]	-	(✓)	✓	-	-	-	-	-
Lin <i>et al.</i> [92]	-	-	-	-	✓	-	-	-
McLean <i>et al.</i> [87]	-	-	(✓)	-	-	-	-	✓
Min <i>et al.</i> [47]	-	-	-	-	-	-	-	-
Oliver <i>et al.</i> [31]	-	(✓)	(✓)	✓	-	-	✓	-
Pang <i>et al.</i> [77]	-	-	✓	-	✓	-	✓	-
Park <i>et al.</i> [90]	-	-	✓	-	-	✓	-	-
Pei <i>et al.</i> [65]	-	✓	✓	-	-	-	-	-
Pop <i>et al.</i> [57]	✓	-	(✓)	-	-	-	Only AVB	-
Raagaard <i>et al.</i> [76]	-	-	(✓)	-	✓	-	-	-
Reusch <i>et al.</i> [52]	-	(✓)	✓	✓	-	-	-	-
Santos <i>et al.</i> [59]	-	✓	✓	✓	-	-	✓	-
Steiner [7]	-	-	✓	-	-	-	✓	-
Steiner <i>et al.</i> [41]	-	(✓)	(✓)	✓	-	-	✓	-
Vlk <i>et al.</i> [48]	-	-	(✓)	-	-	-	-	-
Vlk <i>et al.</i> [51]	-	-	✓	-	-	-	-	-
Wang <i>et al.</i> [50]	-	(✓)	-	-	-	-	-	-
Wang <i>et al.</i> [46]	-	-	✓	✓	-	-	-	-
Wang <i>et al.</i> [78]	-	-	✓	-	✓	-	-	-
Wang <i>et al.</i> [67]	✓	✓	-	-	-	-	-	-
Yao <i>et al.</i> [66]	-	✓	✓	✓	-	-	-	-
Zhang <i>et al.</i> [22]	-	-	-	-	-	-	✓	-
Zhou <i>et al.</i> [63]	-	-	(✓)	-	-	-	-	-

Other research works handle BE traffic by minimizing the flowspan which yields a large time slot at the end of a schedule exclusively for other traffic, e.g., [28], [40], and [62]. Pei et al. [65] evaluate their approach in the presence of BE traffic and rate constrained traffic. Yao et al. [66] consider the joint scheduling of periodic stream without real-time requirements in their approach. The tables indicate works that do not mention BE traffic, but use objective functions that are beneficial to other traffic or that limit the number of guard bands with (✓). For instance, Oliver et al. [31] limit the number of guard bands indirectly by introducing a fixed number of transmission time windows per egress port.

2) QUEUING

Queuing is a controversial topic in the TSN scheduling literature as non-determinism, e.g., frame loss, may cause serious problems. Some research works do not allow queuing at all, e.g., [28], [71], and [96]. The majority of the algorithms in the literature uses frame isolation introduced by [29]. These works are indicated by (✓) in the Tables 2 and 3. Vlk et al. [51] discuss the effects of isolation constraints. They report results indicating that isolation constraints reduce schedulability significantly. Without isolation, the number of scheduled streams can be increased for all evaluated topologies and problem instance sizes. Additionally, isolation

TABLE 3. Overview of considered problem extensions and restrictions in the literature of joint routing approaches.

Research work	AVB	BE	Queuing	Fixed GCL length	Reconfiguration	Reliability	Multicast	Task scheduling
Alnajim <i>et al.</i> [32]	-	✓	✓	-	-	-	-	-
Arestova <i>et al.</i> [103]	-	(✓)	(✓)	-	-	-	-	-
Atallah <i>et al.</i> [113]	-	-	-	-	-	✓	-	-
Atallah <i>et al.</i> [71]	-	-	(✓)	-	-	✓	-	-
Berisa <i>et al.</i> [129]	✓	-	✓	-	-	-	-	-
Bhattacharjee <i>et al.</i> [145]	-	-	(✓)	-	-	-	-	-
Falk <i>et al.</i> [96]	-	-	-	-	-	-	-	-
Falk <i>et al.</i> [108]	-	-	-	-	-	-	-	-
Gavriluț <i>et al.</i> [73]	-	-	-	-	-	✓	✓	-
Gavriluț <i>et al.</i> [123]	✓	-	(✓)	-	-	-	-	-
Gong <i>et al.</i> [143]	-	-	✓	-	-	-	-	-
He <i>et al.</i> [111]	-	-	✓	-	-	-	-	-
Huang <i>et al.</i> [98]	-	-	-	-	✓	-	-	-
Kentis <i>et al.</i> [106]	-	-	✓	-	-	-	-	-
Li <i>et al.</i> [122]	-	-	✓	-	-	✓	✓	-
Li <i>et al.</i> [130]	-	✓	✓	✓	-	-	-	-
Li <i>et al.</i> [81]	-	-	-	-	-	-	-	-
Li <i>et al.</i> [138]	-	-	-	-	✓	-	-	-
Li <i>et al.</i> [133]	-	-	(✓)	-	-	-	✓	-
Mahfouzi <i>et al.</i> [95][140]	-	-	✓	-	-	-	-	✓
Nie <i>et al.</i> [97]	-	-	-	-	-	-	-	-
Pahlevan <i>et al.</i> [104]	-	(✓)	-	-	-	-	-	✓
Pahlevan <i>et al.</i> [100]	-	(✓)	-	-	-	-	-	✓
Pozo <i>et al.</i> [112]	-	-	-	-	-	✓	✓	-
Reusch <i>et al.</i> [55]	-	-	(✓)	-	-	✓	✓	✓
Reusch <i>et al.</i> [72]	-	-	-	-	-	✓	-	✓
Schweissguth <i>et al.</i> [8]	-	-	-	-	-	-	-	-
Schweissguth <i>et al.</i> [132]	-	-	-	-	-	-	✓	-
Smirnov <i>et al.</i> [102]	-	✓	-	-	-	-	✓	-
Syed <i>et al.</i> [116]	-	-	-	-	-	-	-	-
Syed <i>et al.</i> [33]	-	-	-	-	✓	✓	-	-
Syed <i>et al.</i> [135]	-	-	-	-	✓	-	-	-
Syed <i>et al.</i> [115]	-	-	-	-	-	✓	-	-
Syed <i>et al.</i> [117]	-	-	-	-	-	✓	-	-
Vlk <i>et al.</i> [109]	-	-	(✓)	-	-	-	-	-
Wang <i>et al.</i> [107]	-	-	-	-	-	-	-	-
Xu <i>et al.</i> [101]	-	-	(✓)	✓	-	-	-	-
Xu <i>et al.</i> [99]	-	-	(✓)	-	-	-	-	-
Yang <i>et al.</i> [142]	-	-	✓	-	-	-	-	-
Yang <i>et al.</i> [131]	✓	✓	✓	-	-	-	-	-
Yu <i>et al.</i> [134]	-	-	(✓)	✓	-	-	✓	-
Yu <i>et al.</i> [136]	-	-	(✓)	-	✓	-	✓	-
Zhou <i>et al.</i> [118]	-	-	-	-	-	✓	-	-
Zhou <i>et al.</i> [114]	-	-	-	-	-	✓	-	-
Zhou <i>et al.</i> [121]	-	-	✓	-	-	-	-	-
Zhou <i>et al.</i> [141]	-	-	(✓)	-	-	-	-	-

results in larger runtimes compared to scheduling without isolation. In contrast, the differences in end-to-end delays are negligible. However, they propose a different solution to deal with non-determinism, effectively modifying the TAS. Thus, their results are not applicable to current TSN implementations. There are some research works which allow unrestricted queuing, e.g., [59] and [75]. Most of these works do not elaborate on the consequences of unrestricted queuing. In contrast to that, Reusch *et al.* [52], Barzegaran *et al.* [64], and Berisa *et al.* [129] introduced countermeasures for the mentioned consequences. The authors include a worst-case

end-to-end delay analysis in their algorithms such that even in the case of non-determinism, deadlines are met.

3) FIXED GCL LENGTH

Most algorithms presented in the literature handle the generation of GCLs indirectly. They schedule transmission off-sets of frames at end stations and intermediate bridges. The GCLs are generated by a post-processing after scheduling. This step is only mentioned, and the respective authors do not elaborate on it. Examples for such works are [29], [48], and [55]. However, computing GCLs by a post-processing

comes with two drawbacks. First, GCLs have limited size in bridges. Thus, GCLs obtained by a post-processing may not be deployable. Second, the scheduling algorithm cannot include considerations for guard bands. There are some exceptions to this in the literature. Jin et al. [30] present a heuristic to compute schedules with a limited number of GCL entries per egress port. Santos et al. [59] give a detailed SMT model for TSN scheduling which includes the explicit representation of GCLs. Yao et al. [66] limit the number of GCL entries and the maximum queue size in their heuristic, i.e., schedules which do not meet these constraints are not considered valid solutions. Some works limit the number of GCL entries indirectly by introducing transmission windows for egress ports. Streams are mapped to these transmission windows and their number is fixed before scheduling. Examples of such works are [31], [41], and [52]. All schedules for no-wait scheduling can be deployed with a fixed number of GCL entries. As no queuing delay is allowed, frames cannot be scheduled to wait at closed gates. Such a schedule can be deployed by opening all gates for TT traffic at the start of a hyperperiod and never closing them.

4) RECONFIGURATION

In some scenarios it may be infeasible to compute new schedules every time a stream should be integrated into or removed from an existing schedule. For instance, automotive scenarios may include ad-hoc connections between cars and infrastructure. Computing new schedules every time a new stream is added may take too much time, even with heuristic algorithms. Syed et al. [33], [135] consider reconfiguration in such automotive scenarios. Additionally, they also present preliminary work about computing schedules suitable for later reconfiguration in [116]. Raagaard et al. [76] present a heuristic to add streams to an existing schedule. When the heuristic fails, they assign the new stream to other egress queues which were unused before. Pang et al. [77] present work about deploying an updated schedule to a network already executing another schedule. Their approach allows updating the schedule without frame loss or new streams interfering with the old schedule. Another use case for reconfiguration is the reallocation of tasks sending and receiving TT streams. Yu et al. [136] use virtual machines as end stations in their model. These virtual machines may be migrated from one physical device to another, which requires updating schedules and routings. A similar example for reconfiguration is presented in [138]. The authors propose an approach for updating a schedule in case of a permanent end station failure. Schedules and routings must be updated in this case as in [136]. Gärtner et al. [79] introduce a measure for schedule flexibility which also considers deadlines. They use this measure to update schedules in a beneficial way for future updates. Lin et al. [92] show in their evaluations that aligning frame transmissions to the greatest common divisor results in schedules that are suitable for adding streams later.

TABLE 4. Fault models in research works dedicated to reliability.

Fault Model	Research work
Permanent link failure	Atallah <i>et al.</i> [113], Atallah <i>et al.</i> [71], Gavriluț <i>et al.</i> [73], Pozo <i>et al.</i> [112], Reusch <i>et al.</i> [55], Reusch <i>et al.</i> [72], Syed <i>et al.</i> [33], Syed <i>et al.</i> [117]
Frame loss	Atallah <i>et al.</i> [113], Atallah <i>et al.</i> [71], Dobrin <i>et al.</i> [75], Feng <i>et al.</i> [70] [74], Gavriluț <i>et al.</i> [73], Huang <i>et al.</i> [68], Li <i>et al.</i> [122], Park <i>et al.</i> [90], Reusch <i>et al.</i> [55], Reusch <i>et al.</i> [72], Syed <i>et al.</i> [33], Syed <i>et al.</i> [115], Syed <i>et al.</i> [117], Zhou <i>et al.</i> [114]
Clock drift	Craciunas <i>et al.</i> [69]
Hardware bugs	Zhou <i>et al.</i> [118]

5) RELIABILITY

Table 4 compiles fault models used in the literature. The listed research works construct schedules robust in the respective fault model. Computing schedules robust against frame loss is the most common kind of reliability in the TSN scheduling literature. Park et al. [77] handle frame loss by allowing the retransmission of frames. Schedules for such a scenario must schedule enough time between frame transmissions such that retransmissions do not interfere with other frames. Another way to deal with frame loss is proposed by Feng et al. [70], [74]. In contrast to [77], they do not use retransmissions, but they schedule redundant copies of the same stream over the same path. Zhou et al. [114] approximate the probability of frame loss in a joint routing and scheduling model. Redundant copies of streams are routed over not necessarily disjoint paths to reduce the probability of frame loss. Robustness against permanent single link failures are also covered in several works. There are two approaches in the TSN scheduling literature to handles such failures. First, redundant copies of streams are scheduled and routed over link-disjoint paths before a link failure arises. Examples for such works are [33], [71], [73], and [113]. Huang et al. [68] and Syed et al. [115] use Frame Replication and Elimination for Reliability [17] to implement this approach. Second, streams can be rescheduled and rerouted after a link failure occurred. Pozo et al. [112] present a heuristic for fast rescheduling and rerouting in this case. We remark that all works about computing schedules robust against permanent link failures are also robust against frame loss. Both countermeasures against link failures are also effective against frame loss. Another kind of reliability is considered in [69]. The authors compute schedules robust against clock drift, i.e., clocks of different devices running not with the same speed. They introduce gaps between frame transmissions such that the maximum possible clock drift does not affect other frame transmissions. Unknown hardware bugs or deviations from TSN standards are treated by [118]. The proposed algorithm selects expensive bridges with higher certification for paths

of streams with higher safety requirements. In contrast to all other mentioned works with reliability, Syed et al. [117] use an encoding scheme to reconstruct lost frames. The XORed data of two frames is transmitted over a path disjoint to the paths of both frames.

6) MULTICAST

Every algorithm in literature can be used for multicast streams, as a multicast stream can be substituted by a set of unicast streams. However, the number of streams negatively affects the solving time for a problem instance. Tables 2 and 3 indicate multicast support only for works which include some considerations for the efficient integration of multicast streams without introducing a set of new streams. Most such works handle multicast streams by scheduling only a single frame per link, regardless of the number of consecutive links in the multicast tree of the respective stream. Examples for such works are [31], [41], [59], [83], [85], and [128]. An analysis of the joint routing and scheduling problem with multicast streams is presented in [132]. Yu et al. [136] compute routings and schedules for multicast streams such that migrating a virtual machine sending or receiving TT streams can be done easily. Some works allow multicast streams, but do not elaborate on the implementation details, e.g., [22].

7) TASK SCHEDULING

Only a few research works are concerned with the joint scheduling of streams and tasks. Some of them have integrated dependencies between streams and tasks, i.e., tasks can only be scheduled after some stream has arrived. Such works are presented in [83], [84], [85], [87], [88], and [104]. Other works focus on the scheduling of tasks which produce TT streams while considering safety and security considerations. Preliminary results for this scenario are presented in [72] and extended in [55].

8) SECURITY CONSIDERATIONS

While many works focus on the reliability of data transmissions, security aspects were mostly ignored so far. An exception to this are the works of Reusch et al. [55], [72]. The authors identified the problem of replay and impersonation attacks. However, security aspects are not covered by current TSN standards. The authors propose to use the TESLA protocol [146] to mitigate these problems. The additional messages for key exchanges and the additional tasks for verification and key management are considered during scheduling.

B. SCHEDULING OBJECTIVE

Objective functions are used to measure the quality of solutions and to compare them. We discuss common objectives from the literature and classify research works by their objective. Table 5 shows which research work features which kind of objective.

TABLE 5. Categorization of research works based on optimization objectives.

Objective Category	Research work
No objective	Alnajim et al. [32], Ansah et al. [45], Atallah et al. [113], Atallah et al. [71], Bujosa et al. [54], Dai et al. [82], Dobrin et al. [75], Falk et al. [96][108], Farzaneh et al. [93], Gavriluț et al. [128], He et al. [111], Kim et al. [42], Li et al. [130], Li et al. [81], Mahfouzi et al. [95], Mahfouzi et al. [140], Raagaard et al. [76], Santos et al. [59], Steiner [7], Steiner et al. [41], Syed et al. [135] [33] [117], Vlk et al. [48], Wang et al. [78], Wang et al. [46], Xu et al. [99], Yao et al. [66], Zhou et al. [63], Zhou et al. [114], Zhou et al. [121]
Latency and Jitter	Arestova et al. [103] [88], Barzegaran et al. [85], Barzegaran et al. [84], [100], Dürr et al. [28], Feng et al. [70], Gärtner et al. [79][80], Hellmanns et al. [40], Houtan et al. [62], Huang et al. [98], Huang et al. [68], Kim et al. [43][44], McLean et al. [87], Nie et al. [97], Oliver et al. [31], Pahlevan et al. [104], Pang et al. [77], Pei et al. [65], Schweissguth et al. [8] [132], Vlk et al. [51], Wang et al. [50], Yang et al. [131], Zhang et al. [22], Zhou et al. [141]
Queuing	Craciunas et al. [29], Feng et al. [74], Gavriluț et al. [125], Pop et al. [57], Vlk et al. [51], Vlk et al. [109]
Other Traffic	Barzegaran et al. [64], Berisa et al. [129], Gavriluț et al. [125] [123], Houtan et al. [62], Reusch et al. [52], Smirnov et al. [102], Wang et al. [67]
Routing	Li et al. [122], Li et al. [138], Li et al. [133], Schweissguth et al. [132], Wang et al. [107], Yu et al. [134], Yu et al. [136]
Topology Synthesis	Gavriluț et al. [73], Reusch et al. [55], Xu et al. [101], Zhou et al. [118]
Reliability	Craciunas et al. [69], Park et al. [90], Pozo et al. [112]
GCL Synthesis	Kentis et al. [106], Jin et al. [30]
Other	Bhattacharjee et al. [145], Chaîne et al. [53], Feng et al. [83], Ginthör et al. [91], Gong et al. [143], Jin et al. [89], Lin et al. [92], Min et al. [47], Syed et al. [116], Syed et al. [115], Yang et al. [142], Yang et al. [142]

1) NO OBJECTIVE

Many research works have no scheduling objective and only try to find some schedule which fulfills all constraints, e.g., [76], [96], [108], and [111]. We note that many SMT approaches feature no objective [7], [41], [59], [93], [95], [140]. In contrast to ILP solving, SMT solvers were not originally designed for optimization. Therefore, many SMT approaches focus on finding a feasible schedule.

2) LATENCY AND JITTER

TSN and the TAS were designed for traffic with hard real-time requirements. Therefore, latency and jitter of streams are interesting properties of schedules. Objective functions including them are the most common kind of objectives in TSN schedule optimization. Oliver et al. [31] and Barzegaran et al. [84] minimize the per-stream jitter. Minimizing the flowspan, i.e., the time all TT stream arrive

at their destination, is a common objective. Examples of approaches using this objective include [28], [40], [50], [62], [68], [100], [103], and [104]. A related but different objective is the minimization of end-to-end delays of TT streams [8], [51], [65], [77], [79], [131], [132]. Kim et al. [43], [44] minimize multiple objectives weighted by constant factors. They take end-to-end delays, jitter, and bandwidth occupation into account. Barzegaran et al. [85] use a combination of jitter and end-to-end latency as measure of schedule quality. Nie et al. [97] minimize end-to-end latency and transmission offsets simultaneously. We remark that these objectives are not competing, as opposed to most multi-criterion problems. Minimization of transmission offsets is also pursued by [22] and [98] which is related but not equal to flowspan or end-to-end latency minimization. Zhou et al. [141] use a combination of jitter, end-to-end delays, number of scheduled streams, and link utilization.

3) QUEUING

Research works which apply isolation constraints for queuing often use more than one queue per egress port for scheduled traffic. In that way, they are able to schedule more streams as isolation only concern streams in the same egress queue. The assignment of streams to egress queues per egress port is a degree of freedom in the respective scheduling problems. Therefore, they try to minimize the number of queues reserved for TT streams per egress port, as the remaining queues are available for other traffic. Examples for such works include [29], [51], [57], [74], [109], and [125].

4) OTHER TRAFFIC

The schedule of TT streams has an influence on the Quality of Service for other traffic classes. Current approaches for scheduling in TSN focus on AVB traffic and BE traffic. For the joint scheduling of TT and AVB streams, Gavriluț et al. [123], [125] minimize the tardiness of AVB streams as their deadlines are considered to be not strict. Another objective related to AVB streams is used in [129]. The presented heuristic has the objective to schedule as many AVB streams as possible. Yang et al. [131] minimize the weighted sum of stream latencies of scheduled traffic, AVB, and BE streams. Wand et al. [67] use CQF to shape AVB streams in their approach. The objective function aims to load balance the AVB frame transmissions between the time slots of the CQF mechanism. This reduces the probability that non-periodic BE traffic overloads such a slot. The authors of [52] minimize the occupation percentage of egress ports, i.e., the percentage of a hyperperiod with no active transmission window for TT traffic. The rationale of this is that low occupation corresponds to long and frequent time intervals available to other traffic. A similar objective is used in [64] as the authors minimize the average bandwidth occupied by transmission windows for scheduled traffic. Smirnov et al. [102] use a multi-criterion objective for joint routing and scheduling. They reduce the influence of scheduled traffic to other traffic, and simultaneously minimize the number of GCL entries

needed to deploy a schedule. The work in [62] focuses on comparing the influence of different objective functions to the QoS of BE traffic. They propose minimization and maximization of frame offsets, hoping that grouping frames together increases the QoS. Additionally, they also suggest two objectives which maximize the gaps between consecutive frame transmissions on a link. They assume that starvation of other traffic classes is reduced in this way.

5) ROUTING

Research works about joint routing and scheduling often consider the quality of the routing in their objective. All of them have in common that the length of the paths is minimized. This is reasonable as longer paths correspond to higher link utilizations, end-to-end latencies, and harder scheduling instances. Schweissguth et al. [132] propose a multi-objective optimization for joint routing and scheduling. First, routing and schedule with minimized path lengths are computed. The obtained path lengths are used as maximum path lengths per stream in a second run. The second run minimizes end-to-end latencies. The joint routing approach of [107] minimizes the number of links in the routing. Li et al. [138] simultaneously minimize the path lengths and a measure for scheduling conflicts of streams routed over the same link. Yu et al. [134] schedule and route streams one after another. They minimize a weighted sum of the number of links used for the currently scheduled stream, and the bandwidth utilization. Li et al. [133] simultaneously minimize path lengths in the routing, and the flowspan. Yu et al. [136] consider the migration of sources of TT streams. They minimize the maximum distance from all possible source nodes of a stream to all destination nodes in a multicast tree. Li et al. [122] maximize the number of streams which are scheduled and routed, and also try to minimize the maximum link load as a secondary objective.

6) TOPOLOGY SYNTHESIS

In addition to joint routing and scheduling, some works also construct the network topology. TSN bridges are expensive, and thus such objectives always include costs for bridges. Gavriluț et al. [73] minimize multiple objectives weighted by constant factors. The first objective is the tardiness of TT streams to guide their GRASP heuristic to solutions with no deadline misses. The second objective is topology costs. A similar objective is used in [55]. The weighted sum of routing and schedule costs is minimized. Routing costs constitute of overlap penalties for redundant paths and path lengths. Schedule costs constitute of punishments for not schedulable streams and stream latencies. Another approach which minimizes topology costs is proposed in [118]. Selecting bridges from a library is part of the presented problem, which imposes costs for bridges and additional costs when multiple vendors are used. Xu et al. [101] minimize the number of bridges needed to schedule and route all streams such that the utilization is maximized.

7) RELIABILITY

Reliability requirements can be ensured by constraining the set of feasible solutions. However, some works choose to maximize reliability for their respective fault model. Pozo et al. [112] maximize the idle times of links and frames, as such schedules are easier to repair upon link failure. Craciunas et al. [69] maximize the allowed out-of-sync clock drift to cope with synchronization problems and maximize robustness against clock drift. Park et al. [90] maximize the number of times a frame can be retransmitted without missing its deadline, as they include preemption in their model.

8) GCL SYNTHESIS

TSN bridges do not have an unlimited number of GCL entries per egress port. The minimization of GCL entries is considered by [30]. The reason for this is that the authors propose an incremental approach and the overall number of needed GCL entries is not known in advance. Reducing the number of gate events also reduces the number of guard bands which is beneficial for BE traffic. Kentis et al. [106] minimize the GCL schedule duration. However, it is not clear why schedule duration matters, as the limiting factor in TSN hardware is the number of GCL entries.

9) OTHERS

Some research works use a problem specific objective not comparable to other works. We present them for the sake of completeness. The authors of [89] minimize the number of frames as they propose a joint approach for scheduling and message fragmentation. Syed et al. [115] and [116] use a modelling specific objective which is related to load balancing of ports in an in-vehicle architecture with one central processing unit. Ginthür et al. [91] minimize the wasted bandwidth for different link layer technologies, i.e., Ethernet and 5G links. Feng et al. [83] minimize the response time of tasks which may be dependent on streams as they consider the joint scheduling of streams and tasks. Chaine et al. [110] maximize the length of transmission time windows of streams at their respective talkers such that latency and jitter requirements are met. This is the only work in TSN scheduling which employs a quadratic objective function. Bhattacharjee et al. [145] employ a multi-criterion objective. Their first objective is to minimize the maximum load across all servers as the considered problem includes the placement of talker applications. The second objective is to minimize the average hop count of all streams. Lin et al. [92] present a heuristic for incremental scheduling that aims to maximize the probability that more streams can be added later. This is required in industrial use cases as turning off machines to deploy a new schedule may be expensive. Yang et al. [142] state that they maximize the number of scheduled streams while minimizing the link occupancy rate. However, this rate is not defined in the published magazine article. Gong et al. [143] also maximize the occupancy rate while minimizing the maximum link utilization. They define the occupancy rate as the fraction

TABLE 6. Overview of investigated problem instances in the literature of the scheduling problem with fixed routing.

Research work	Topology	ES	Bridges	TT streams
Arestova et al. [88]	Mesh, ring	N/A	5 – 30	N/A
Barzegaran et al. [85]	Various	6 – 20	2 – 20	8 – 27
Barzegaran et al. [64]	Various	3 – 31	2 – 15	7 – 137
Barzegaran et al. [84]	Various	5 – 20	2 – 20	8 – 27
Bujosa et al. [54]	Line	3 – 9	1 – 3	N/A
Chaine et al. [53]	Line, spacecraft	2 – 31	4 – 15	15 – 304
Craciunas et al. [29]	N/A	3–7	1–5	5–1000
Craciunas et al. [69]	Tree	16	7	96
Dai et al. [82]	Link	N/A	N/A	3
Dürr et al. [28]	ER, RRG, BA	24–100	5–20	30–1500
Farzaneh et al. [93]	Snowflake	12	2	14–100
Feng et al. [70]	N/A	2 – 8	2 – 5	2 – 16
Feng et al. [74]	N/A	5 – 8	3 – 5	N/A
Feng et al. [83]	N/A	50	10	11
Gärtner et al. [79][80]	Line, machine	2 – 54	2 – 15	1 – 104
Gavriluț et al. [125]	Star, Snowflake	3–32	1–18	4–35
Gavriluț et al. [128]	Various	7–31	1–15	20–186
Ginthür et al. [91]	N/A	N/A	N/A	10
Hellmanns et al. [40]	Ring of rings	100–2500		10–2000
Hellmanns et al. [144]	Ring of rings	N/A	N/A	50–500
Houtan et al. [62]	Snowflake	6	2	10
Huang et al. [68]	Automotive	33	14	20 – 480
Jin et al. [89]	N/A	5–30	5–30	10–60
Jin et al. [30]	N/A	N/A	6–20	10–10000
Kim et al. [42]	Various	7	5	6
Kim et al. [43][44]	Automotive	17	4	27
Li et al. [81]	Various	30 – 100	7 – 20	3 – 100
Lin et al. [92]	Tree, mesh, ring	4 – 16	1 – 4	~ 48 – 223
McLean et al. [87]	Tree, mesh, ring	4 – 432	2 – 43	16 – 1728
Min et al. [47]	Real-world		14	300
Oliver et al. [31]	Line	50	10	10–50
Pang et al. [77]	In-train, spacecraft	31 – 54	13 – 31	N/A
Park et al. [90]	Automotive	5 – 20	3 – 7	100 – 500
Pei et al. [65]	Spacecraft	31	15	20
Pop et al. [57]	N/A	3–5	1–2	3–5
Raagaard et al. [76]	N/A		4–402	15–290
Reusch et al. [72]	Various	4–32	1–16	N/A
Reusch et al. [52]	Snowflake	3–256	1–146	14–316
Santos et al. [59]	N/A	50	10	1 – 10
Steiner [7]	Star, tree, snowflake	N/A	N/A	100 – 1000
Steiner et al. [41]	N/A	50	10	10–50
Vlk et al. [48]	Ring of lines, ring of trees, spacecraft	~ 20 – 1700	~ 20 – 300	1500 – 12000
Vlk et al. [51]	Mesh, ring, tree	4 – 16	1 – 4	6 – 450
Wang et al. [50]	N/A	4 – 10	3 – 9	10 – 100
Wang et al. [46]	Automotive	4	1	3
Wang et al. [78]	Mesh	15 – 16	6 – 8	N/A
Wang et al. [67]	Line, ring, tree	N/A	5 – 200	N/A
Yao et al. [66]	N/A	N/A	N/A	10 – 20
Zhou et al. [63]	Automotive	5	16	N/A
Zhang et al. [22]	Tree, line, tree		6 – 8	200 – 1200

of bandwidth reserved for scheduled traffic actually used for transmissions. Min et al. [47] compare metaheuristics by maximizing the number of scheduled stream for the same problem instance.

TABLE 7. Overview of investigated problem instances in the literature of the joint routing problem.

Research work	Topology	ES	Bridges	TT streams
Alnajim <i>et al.</i> [32]	N/A	30–150	10–50	100–1500
Arestova <i>et al.</i> [103]	N/A	50	10	10–100
Atallah <i>et al.</i> [113]	N/A	6–24	N/A	30–600
Atallah <i>et al.</i> [71]	N/A	N/A	3–21	20–60
Berisa <i>et al.</i> [129]	Ring, full mesh, spacecraft	13–31	4–15	222
Bhattacharjee <i>et al.</i> [145]	Ring, BA, ER	46–1024	24–512	90–1845
Falk <i>et al.</i> [96]	Line, ring, BA, ER	5–36		2–30
Falk <i>et al.</i> [108]	Ring w/ k neighbors	50–400		50–150
Gavriluț <i>et al.</i> [73]	N/A	4–20	N/A	4–38
Gavriluț <i>et al.</i> [123]	Various	3–256	2–146	4–427
Gong <i>et al.</i> [143]	N/A	N/A	N/A	15–180
He <i>et al.</i> [111]	ER, RRG, BA	20		25–200
Huang <i>et al.</i> [98]	Spacecraft, ER	N/A	N/A	500–2000
Kentis <i>et al.</i> [106]	Ring, mesh	12	12	20–52
Li <i>et al.</i> [122]	ER, RRG, BA	10	10	10–100
Li <i>et al.</i> [130]	Mesh, automotive	15–105	3–21	2–4000
Li <i>et al.</i> [138]	Real-world	31	13	100–300
Li <i>et al.</i> [133]	N/A	39	16	10–40
Mahfouzi <i>et al.</i> [95][140]	ER, Automotive	20	10–45	19–106
Nie <i>et al.</i> [97]	Ring, mesh	11–14	4–15	10–40
Pahlevan <i>et al.</i> [104]	Grid, ring	27–45	9	30–40
Pahlevan <i>et al.</i> [100]	Grid, ring	50	10	60–100
Pozo <i>et al.</i> [112]	Synthetic	6–8	3–8	10–50
Reusch <i>et al.</i> [55]	Various	4–128	2–64	2–144
Reusch <i>et al.</i> [72]	Various	4–32	1–16	N/A
Schweissguth <i>et al.</i> [8]	Ring, mesh	13	N/A	60
Schweissguth <i>et al.</i> [132]	Ring, mesh	12	12	25–40
Smirnov <i>et al.</i> [102]	N/A	N/A	N/A	5–75
Syed <i>et al.</i> [116]	Automotive	N/A	N/A	20–90
Syed <i>et al.</i> [135]	Automotive	N/A	N/A	100–500
Syed <i>et al.</i> [33]	Automotive	N/A	N/A	100–500
Syed <i>et al.</i> [115]	Automotive	N/A	N/A	20–90
Syed <i>et al.</i> [117]	Automotive	N/A	N/A	112
Vlk <i>et al.</i> [109]	Ring, mesh	12–48	12–48	10–300
Wang <i>et al.</i> [107]	N/A	25	5	10–100
Xu <i>et al.</i> [101]	Mesh	5	1–23	4–12
Xu <i>et al.</i> [99]	Mesh, ring	N/A	7–15	40–80
Yang <i>et al.</i> [142]	N/A	2	N/A	45–180
Yang <i>et al.</i> [131]	Star, tree, BA	N/A	8–18	150–900
Yu <i>et al.</i> [134]	Mesh	72	24	1–500
Yu <i>et al.</i> [136]	BA	72	24	10–350
Zhou <i>et al.</i> [118]	ER, automotive	N/A	6–10	50–240
Zhou <i>et al.</i> [114]	ER, automotive	16	6–10	50–380
Zhou <i>et al.</i> [121]	ER, real-world	16	4–64	30–220
Zhou <i>et al.</i> [141]	Mesh	≥ 4	3–15	50–650

C. PROBLEM INSTANCES

Before we describe evaluation results, we describe the problem instances used for evaluations in the literature. We present an overview of used network topologies, network sizes, and numbers of streams. Tables 6 and 7 compile this information about the problem instances used for evaluations with fixed routing and joint routing, respectively.

Unfortunately, some research works do not elaborate on the used topologies, which makes assessing and comparing the results to other works harder. Most research works only use synthetic test cases. Ring topologies are commonly used in evaluations, e.g., in [8], [40], [67], [87], [88], [96], [97], [100], [101], [104], [108], [109], and [132]. Hellmanns *et al.* [40] argue that rings are a common topology in real-world industrial facilities. Other systematic topologies used include line [31], [67], [96], grid [100], [104], and snowflake-like [52], [62], [93], [125] networks. Various randomly generated topologies are also used in evaluations. Erdős-Rényi graphs (ER) are the most common ones [28], [96], [111], [114] [118], [121], [122], but Barabási-Albert graphs (BA) [28], [96], [111], [122] [134] and random regular graphs (RRG) [28], [111], [122] are also used. A few research works features evaluations with real-world topologies. Syed *et al.* [33], [115], [116], [117], [135] use a real-world automotive architecture for their evaluations. A large automotive architecture including stream parameters is discussed in [68]. Other automotive architectures are used by Kim *et al.* [43], [44], Li *et al.* [130], Mahfouzi *et al.* [95], [140], and Wang *et al.* [46]. Zhou *et al.* [114], [118] conclude their evaluations by investigating a real-world example from General Motors. The authors of [73] also use a real-world problem instance from General Motors. However, this instance is only a set of streams without topology. Min *et al.* [47] use the network topology of the National Science Foundation of the United States of America. Barzegaran *et al.* [64] presents evaluations with real-world test cases from General Motors and a real-world spacecraft. Pang *et al.* [77] evaluate an algorithm for schedule updates in a real-world in-train network and a spacecraft. Similarly, the authors of [79] evaluate their algorithm for schedule reconfigurations with the topology of a not specified machine. Vlk *et al.* [48], Chaine *et al.* [53], Huang *et al.* [98], Gavriluț *et al.* [128], and Berisa *et al.* [129], perform evaluations with a real-world spacecraft topology.

All research works concerned with synthetic test cases use randomly generated streams. Sources and destinations of these streams are selected uniformly from the sets of talkers and listeners in the respective topology. The number of streams varies considerably between different research works. It ranges from 2 streams in the smallest instance of Falk *et al.* [96] to up to 10812 streams in the largest instance of Vlk *et al.* [48]. All works, which describe the placement of deadlines, place them at the end of the respective stream's period. No research work allows deadlines to be after the end of the hyperperiod a frame was sent. Stream periods range from $32 \mu\text{s}$ in [30] to 500ms in [29]. All research works assume transmission rates of either 100 Mb/s or 1 Gb/s per egress port.

D. SCALABILITY

Scheduling in TSN is known to be NP-complete. Therefore, solving times and sizes of feasible problem instances matter. Almost all research works about TSN scheduling include

or even focus on evaluating the scalability of the respective proposed approach. These evaluations measure the solving times for selected problem instances. Tables 8 and 9 compile the reported runtimes needed to solve the largest problem instance for which a schedule was found in the respective research work. Tables 10 and 11 report the same results for research works which feature the joint computation of schedules and routings. We divided results in separate tables for exact and heuristic algorithms for better comparability. In cases where it was not clear which problem instance can be considered as the largest one, we used the number of streams as tie-breaker. This is justified by several research works surveyed in this paper, e.g., in [96]. The tables are meant to show general tendencies and improvements, not to suggest one approach over the other. Caution is needed when interpreting the tables. It shows the reported times after which an algorithm terminated, not the time until a first valid schedule was obtained, as almost all papers do not report this time. This is a systematic disadvantage of exact approaches as they only terminate when the optimal solution is found or some timeout is reached, while heuristic algorithms may terminate much earlier with suboptimal solutions. Some research works deal with more parameters than the size of the network and the number of streams, e.g., Oliver et al. [31] present evaluations about the influence of the number of transmission windows per egress port to scalability. Other works handle problem extensions, e.g., AVB or task scheduling. Approximations are given when results are not stated in the text and had to be estimated by the presented figures. Ranges are given when multiple instances are considered to be the largest. We identified two tendencies with respect to solving times.

First, heuristic approaches can handle larger instances than approaches with exact solution methods. While the number of network nodes is approximately in the same range, heuristic algorithms can schedule problem instances with more streams compared to exact approaches. Typical numbers of streams in exact approaches are less than 100, e.g., in [8], [69], and [96]. However, there are some notable exceptions. Craciunas et al. [29] present an incremental scheduling algorithm with backtracking, which scheduled instances with 1000 streams in their evaluations. Later works present incremental approaches which were able to schedule as many as 2000 streams [98]. Oliver et al. [31] assigned streams to transmission windows of egress ports and report solved instances with 750 streams. Heuristic approaches were able to schedule instances with more than 10000 streams, e.g., [48] and [30].

Second, exact approaches which solve the joint routing and scheduling problem can only handle instances with smaller numbers of nodes compared to approaches solely for scheduling. Typical networks in evaluations of joint routing algorithms contain less than 50 nodes [71], [72], [73]. This is due to the solution space growing heavily with an increased number of possible paths per stream. However, there are approaches able to compute routings and schedules

TABLE 8. Overview of solving times of the respective largest reported problem instance for which a schedule was found. Only research works with exact approach and fixed routing are included for comparability.

Research work	Solution approach	Nodes	TT streams	Runtime (s)
Barzegaran <i>et al.</i> [64]	CP	120	500	N/A
Barzegaran <i>et al.</i> [84]	CP	40	27	2563
Chaîne <i>et al.</i> [53]	ILP	46	304	~ 240
Craciunas <i>et al.</i> [29]	SMT	12	1000	< 18000
Craciunas <i>et al.</i> [69]	SMT	23	96	~ 0.343 – 0.437
Dai <i>et al.</i> [82]	CP	N/A	3	N/A
Farzaneh <i>et al.</i> [93]	SMT	14	100	< 240
Feng <i>et al.</i> [70]	SMT	13	16	N/A
Feng <i>et al.</i> [74]	SMT	13	N/A	~ 900
Feng <i>et al.</i> [83]	SMT	60	11	384 – 694
Ginhör <i>et al.</i> [91]	CP	N/A	10	N/A
Houtan <i>et al.</i> [62]	SMT	8	10	0.37–1153.52
Jin <i>et al.</i> [89]	SMT	4	4	< 600
Jin <i>et al.</i> [30]	SMT	6	50	660–1080
Li <i>et al.</i> [81]	SMT	120	100	~ 320 – 450
Nie <i>et al.</i> [97]	ILP	26	40	~ 0 – 10
Oliver <i>et al.</i> [31]	SMT	20	750	~ 600
Pang <i>et al.</i> [77]	ILP	86	N/A	~ 620 – 900
Pop <i>et al.</i> [57]	ILP	7	5	80.19
Santos <i>et al.</i> [59]	SMT	60	10	< 288000
Steiner [7]	SMT	N/A	1000	~ 180 – 1140
Steiner <i>et al.</i> [41]	SMT	60	50	~ 0.01 – 100
Vlk <i>et al.</i> [51]	ILP	20	414	≤ 600
Zhou <i>et al.</i> [63]	SMT	21	N/A	N/A

TABLE 9. Overview of solving times of the respective largest reported problem instance for which a schedule was found. Only research works with heuristic approach and fixed routing are included for comparability.

Research work	Solution approach	Nodes	TT streams	Runtime (s)
Arestova <i>et al.</i> [88]	Heuristic	> 30	N/A	105.4
Atallah <i>et al.</i> [113]	Heuristic	24	600	~ 8
Barzegaran <i>et al.</i> [85]	CP + heuristic	40	27	3553 – 9153
Barzegaran <i>et al.</i> [84]	CP + heuristic	40	27	161
Bujosa <i>et al.</i> [54]	Heuristic	12	N/A	< 0.01
Dürr <i>et al.</i> [28]	Tabu search	120	1500	11520
Gärtner <i>et al.</i> [79][80]	Heuristic	69	104	~ 0.1
Gavriluț <i>et al.</i> [125]	GRASP	50	35	612.8
Gavriluț <i>et al.</i> [128]	GRASP	46	186	750
Hellmanns <i>et al.</i> [40]	Tabu search	2500	2000	~ 4400
Huang <i>et al.</i> [68]	Heuristic	47	480	~ 2700
Jin <i>et al.</i> [30]	Heuristic	20	10000	~ 5100
Kim <i>et al.</i> [42]	Heuristic	12	6	N/A
Kim <i>et al.</i> [43][44]	GA	21	27	12300
Lin <i>et al.</i> [92]	Heuristic	20	~ 223	N/A
McLean <i>et al.</i> [87]	Heuristic	475	1728	~ 10000
Park <i>et al.</i> [90]	GA	< 27	500	N/A
Pei <i>et al.</i> [65]	Heuristic	46	20	N/A
Raagaard <i>et al.</i> [76]	Heuristic	402	290	20–54
Reusch <i>et al.</i> [52]	Heuristic	402	316	10.52
Vlk <i>et al.</i> [48]	Heuristic	2000	10812	~ 1000
Wang <i>et al.</i> [50]	Machine learning	19	100	~ 400
Wang <i>et al.</i> [46]	Heuristic	5	3	< 1
Wang <i>et al.</i> [78]	Heuristic	23	N/A	N/A
Wang <i>et al.</i> [67]	Heuristic	16	200	~ 1000
Yao <i>et al.</i> [66]	Heuristic	N/A	20	~ 2
Zhang <i>et al.</i> [22]	Heuristic	8	1200	~ 11

for problem instances with up to 96 nodes [109], [134]. Most networks in the literature of scheduling with a fixed routing contain less than 96 nodes. The range of the number of

TABLE 10. Overview of solving times of the respective largest reported problem instance for which a schedule was found. Only research works with exact approach and joint routing are included for comparability.

Research work	Solution Approach	Nodes	TT streams	Runtime (s)
Atallah <i>et al.</i> [71]	ILP	14	60	~ 100
Falk <i>et al.</i> [96]	ILP	8	30	~ 170 – 1580
Gavriluț <i>et al.</i> [73]	CP	20	38	172800
Hellmanns <i>et al.</i> [144]	ILP	N/A	N/A	50–500
Huang <i>et al.</i> [98]	ILP	44	2000	1620
Li <i>et al.</i> [133]	ILP	55	40	~ 80
Mahfouzi <i>et al.</i> [95][140]	SMT	65	45	~ 21
Pozo <i>et al.</i> [112]	ILP	16	50	2–85
Reusch <i>et al.</i> [55]	CP	48	33	1500
Reusch <i>et al.</i> [72]	CP	48	N/A	~ 1800
Schweissguth <i>et al.</i> [8]	ILP	24	52	1284.53
Schweissguth <i>et al.</i> [132]	ILP	24	~ 46 – 60	N/A
Smirnov <i>et al.</i> [102]	PBO	N/A	75	~ 42 – 78
Syed <i>et al.</i> [116]	ILP	N/A	90	~ 21000
Vlk <i>et al.</i> [109]	CP	96	300	~ 100
Xu <i>et al.</i> [101]	SMT	24	12	~ 144000
Xu <i>et al.</i> [99]	SMT	12	80	~ 850
Yu <i>et al.</i> [134]	ILP	96	450	N/A
Zhou <i>et al.</i> [118]	SMT	10	240	~ 3500 – 4000
Zhou <i>et al.</i> [114]	SMT	10	380	~ 2700
Zhou <i>et al.</i> [121]	SMT	24	220	~ 55 – 440

streams is approximately the same for approaches with fixed routing and joint routing.

VI. PUBLICATION HISTORY

We give an overview of the publication history of TSN scheduling. First, we highlight seminal works from the literature. Then, we analyze the development of the field with respect to the number of published papers per year.

A. SEMINAL WORKS

Early works about per-flow scheduling in Ethernet networks were presented by Steiner [7] and Schweissguth *et al.* [8]. While these works are not specifically for TSN and abstract on the details of the real-time enhancement for Ethernet, they influenced many later works presented in this survey. The first works specifically about scheduling in TSN were presented in 2016. Dürr *et al.* [28] presented an ILP for no-wait scheduling and identified the problem of guard bands consuming bandwidth. Craciunas *et al.* [29] adapted the work of Steiner [7] for TSN. They introduced isolation constraints and incremental scheduling to the domain of TSN. Gavriluț *et al.* [73] is the first work which features joint routing and reliability considerations. Raagard *et al.* [76] introduced reconfiguration of schedules to TSN scheduling. Oliver *et al.* [31] proposed a scheduling approach with limits the number of used GCL entries by computing them in a joint approach with transmission offsets. All earlier works computed GCLs by a post-processing after scheduling.

B. PUBLISHED PAPERS

Figure 19 shows the number of papers about TSN scheduling per year. The first papers about scheduling in TSN were published in 2016. The general trend is that the field grows

TABLE 11. Overview of solving times of the respective largest reported problem instance for which a schedule was found. Only research works with heuristic approach and joint routing are included for comparability.

Research work	Solution Approach	Nodes	TT streams	Runtime (s)
Alnajim <i>et al.</i> [32]	Heuristic	200	1500	2718
Arestova <i>et al.</i> [103]	Genetic algorithm	60	100	~ 470
Berisa <i>et al.</i> [129]	Heuristic	46	222	602 – 7090
Bhattacharjee <i>et al.</i> [145]	SA	1536	1845	~ 1800
Falk <i>et al.</i> [108]	Heuristic	400	400	~ 6000 – 11000
Gavriluț <i>et al.</i> [123]	GRASP	402	427	534.6
Gavriluț <i>et al.</i> [73]	GRASP	20	38	558
	Heuristic	20	38	130
Gong <i>et al.</i> [143]	Tabu search	N/A	180	~ 11160
He <i>et al.</i> [111]	Machine learning	20	200	7
Kentis <i>et al.</i> [106]	Heuristic	≥ 13	60	N/A
Li <i>et al.</i> [122]	Heuristic	20	100	N/A
Li <i>et al.</i> [130]	Heuristic	126	4000	0.437 – 0.88
Li <i>et al.</i> [138]	ILP + heuristic	44	300	~ 0.3
Pahlevan <i>et al.</i> [104]	List scheduler	45	40	0.014
	Genetic algorithm	45	40	56.75
Pahlevan <i>et al.</i> [100]	List scheduler	50	100	0.103
	Heuristic	50	100	1.58
Reusch <i>et al.</i> [55]	SA + list scheduler	192	144	1200
Syed <i>et al.</i> [33]	Heuristic	N/A	500	0.41
Syed <i>et al.</i> [135]	Heuristic	N/A	500	0.170
Syed <i>et al.</i> [115]	Heuristic	N/A	90	~ 342
Syed <i>et al.</i> [117]	Heuristic	N/A	90	~ 8 – 10
Wang <i>et al.</i> [107]	Heuristic	30	100	72
Yang <i>et al.</i> [142]	Tabu search	N/A	180	~ 11160
Yang <i>et al.</i> [131]	Machine learning	18	900	N/A
Yu <i>et al.</i> [136]	Heuristic	96	350	N/A
Zhou <i>et al.</i> [141]	Heuristic	N/A	650	~ 2700

almost monotonously from one year to the next, with only one exception in 2019. We observe a significant increase in published works since the year 2020. Given the fast growth of the last 2 years, we expect even more research works about TSN scheduling in the future.

VII. FUTURE WORKS

In this section, we discuss the results of the literature study. First, we suggest improvements for future research works. Then, we highlight open problems not handled sufficiently so far.

A. SUGGESTIONS FOR IMPROVEMENT

The surveyed literature features many high quality research works. However, there is room for improvement in the presentation of some of these works. We suggest improvements in the hope that the overall quality of the TSN scheduling literature can be improved even more in the future. First, we discuss shortcomings and improvements in the presentation of evaluation methodologies. Then, we suggest the use of the technical terminology used in Ethernet bridging.

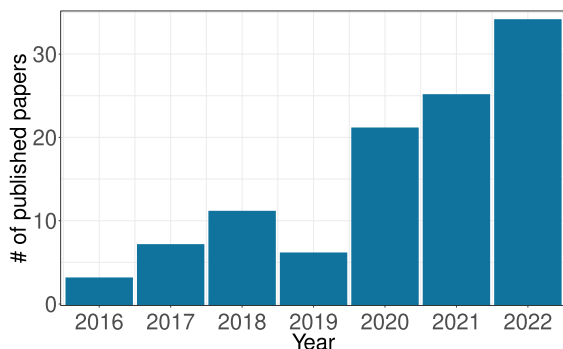


FIGURE 19. Number of published research works per year about TSN scheduling. Only works published before March 2023 are counted.

1) EVALUATION METHODOLOGIES

The scalability of the proposed solutions from the literature was extensively evaluated. Unfortunately, the impact of possible additional features and changes in parameters to the various objective functions was mostly ignored so far. Although scalability is an important property of a scheduling algorithm, it would be interesting to see more evaluations regarding solution quality. Most test cases in the literature are synthetically constructed, both network topology and streams. Even though it is hard to obtain test cases from the industry, let alone publish them, we would like to see more evaluations with realistic instances. It is not clear whether the proposed algorithms are suitable for large industry-scale instances or how they look like. It is also extremely difficult to compare the results of different research works as there is no public set of test cases for benchmarks. Consequently, there is little research work available about which algorithm should be used in which setting.

Unfortunately, it is also hard to assess the significance of evaluation results in some papers for two reasons. First, the instances solved are not sufficiently described. At least the topology and a description of assumed delays, e.g., processing and propagation delay, should be contained in the description of the network. Important properties of streams like deadlines or periods are often missing. Second, some evaluations report results for individual problem instances and are thus more of anecdotal character. There are easy and hard instances for every algorithm. Comparing multiple approaches on the same selected instances can be useful, but this may have the taste of picking specific instances in support of some conclusion. Instead of reporting results for individual instances, average results for multiple instances with the same evaluation setting should be reported. However, we acknowledge that evaluations for specific scenarios can be of interest. Especially readers from the industry may enjoy a rigorous report about a specific running system. We only want to emphasize that strong conclusions should be backed up by strong evidence and extensive evaluation. Another property covered by many evaluations is the schedulability of the respective proposed approach. These evaluations treat

instances as infeasible when no schedule was found before some timeout. Thus, comparing the schedulability of two scheduling approaches which support different features is biased, as timeouts do not prove infeasibility. This may lead to wrong conclusions in favor of some algorithm or model, although schedulability is actually equal.

2) TERMINOLOGY

Many works surveyed in this paper use a vocabulary loosely related to Ethernet bridging. However, the standards and other relevant literature use a specific technical terminology. We suggest that the scheduling community adopts this jargon. Readers from adjacent research domains or who have prior knowledge in Ethernet bridging can benefit from a consistent vocabulary. The word *stream* is used in several standards, e.g., [11], [12], and [147]. Therefore, we suggest to use *stream* instead of *flow*. Network devices which send or receive data streams are denoted as *end stations* in the original bridging standard IEEE 802.1D [148]. The source end station of a stream is denoted as *talker*, while the destination end station is denoted as *listener*. Layer 2 switching devices are denoted as *bridges* instead of *switches* in IEEE 802.1D [148] and in the names of many other standards, e.g., in [9] and [14]. Thus, we suggest to use these terms when describing network topologies.

Frames are the units of data transmission, as TSN is a layer 2 technology, while packets are the units of data transmissions in layer 3 technologies (cf. [149]). Although the meaning of the term *packet* is clear in the context of scheduling, it is technically wrong. Routing is the process of path computation on layer 3. Therefore, the term *path selection* is more appropriate in TSN. However, we note that we used the term *routing* in this survey several times. The reason for this is to ensure consistency with the reviewed literature which solves the so-called joint routing problem.

B. OPEN PROBLEMS

The available literature is comprehensive with regard to solution approaches to the unmodified scheduling problem in TSN. However, there is still a wide field of relevant aspects which are not yet understood.

1) IMPACT OF GUARD BANDS AND GCL ENTRIES

To the best of our knowledge, the impact of guard bands on bandwidth available to lower-priority traffic was not evaluated in the literature. Likewise, the impact of available GCL entries on available bandwidth for lower-priority traffic is not investigated in detail. The evaluations so far suggest that AVB streams benefit from schedules with many holes between TT streams with regard to tardiness. However, such schedules may need more gate closings and thus guard bands, which reduces the available bandwidth. It is not clear how AVB and BE traffic can be simultaneously integrated in a unified approach for the scheduling of TT streams.

2) ROUTING AND MULTICAST

The joint routing and scheduling problem was explored in detail in the literature. All research works about this topic agree that schedulability benefits from joint routing and scheduling. However, solving the joint routing problem is significantly harder compared to scheduling with a given routing. Unfortunately, there is currently no exact and scalable approach known for joint routing. Additionally, it is not understood which properties a routing should have to benefit schedule synthesis and quality. TSN supports multicast streams which are relevant in real use cases. Some of the algorithms presented in research works covered by this survey can handle multicast streams. However, the literature lacks evaluations and insights about the appropriate integration of multicast streams in a schedule.

3) ONLINE RECONFIGURATION

There is also little work about online schedule reconfiguration, though it is important for operation. In some scenarios, e.g., automotive networks, insertion and removal of streams at execution time of the schedule can be important. So far it is not explored exhaustively what properties a schedule should have such that reconfiguration can be computed efficiently. However, there are preliminary works about this topic [79], [116]. Instead of rescheduling all streams, many works about reconfiguration try to resolve conflicts by assigning streams to other traffic classes [76] or paths [136], [138]. Other ways to resolve scheduling conflicts instead of rescheduling all streams may be needed in the future. Unfortunately, there are no reconfiguration algorithms for most of the problem extensions from Section III-E.

4) QUEUING AND HANDLING OF NON-DETERMINISM

An important open problem in TSN is sufficient integration of queuing. Almost all research works use isolation constraints from [29], i.e., they do not allow frames of different streams to reside in the same queue at the same time. However, this is not a requirement of the TAS. Some approaches even separate streams by assigning them to different egress queues during scheduling. The rationale of this is to reduce the impact of non-determinism like frame loss. Other attempts to reduce the influence of such causes of non-determinism are not yet explored. The benefits of unrestricted queuing regarding schedulability or solution quality has not yet been evaluated.

Real hardware bridges are subject to non-determinism. There is jitter in processing delays, and clocks are not exactly synchronized in reality. Additionally, frames that are scheduled to arrive approximately at the same time at two ingress ports of the same bridge may cause race conditions, i.e., processing order is not deterministic. All research works covered by this survey assume bridges are perfectly deterministic. Thus, the literature lacks handling of such causes of non-determinism.

5) FILTERING AND POLICING

Per-Stream Filtering and Policing (PSFP) is a standard defined in IEEE 802.1Qci [147] for filtering and policing in TSN. Currently, there are no devices available implementing PSFP. However, filtering and policing could be used to prevent violations of schedules through unexpected packets. Packets not scheduled, delayed frames, and frames larger than expected can be filtered at execution time of a schedule. Thus, PSFP requires configuration of filtering entries that need to be derived from the schedule. A joint approach may be needed as PSFP imposes additional restrictions, e.g., the number of available filtering entries will be limited in bridges.

6) SECURITY ASPECTS

The security of real-time Ethernet networks was mostly ignored so far. All considerations for reliability and safety in TSN assume that no malicious party is involved in the communication. The standards do not cover countermeasures against replay or impersonation attacks. This may be a problem for highly vulnerable use cases of TSN, e.g., factory automation and in-vehicle networks. Future scheduling algorithms may integrate security considerations. For instance, key exchange and management result in additional streams that must be protected from other traffic. However, source authentication and integrity may also be implemented by future TSN standards or application layer protocols. Other security problems may be countered with PSFP, e.g., jamming and Denial-of-Service attacks by malicious end stations.

7) LEGACY DEVICES

Traditional Ethernet is a widespread layer 2 technology for industrial applications. Such applications are typically designed to be used for years or even decades. Thus, integrating legacy devices which are not capable of traffic scheduling or time synchronization will be a major problem in the next years for the deployment of TSN. Future scheduling algorithms may help to integrate such devices. For instance, scheduling algorithms can reserve bandwidth for the communication of these devices. However, new devices, e.g., gateways or proxies, may be needed to fully support the coexistence of legacy devices and scheduled traffic.

8) USE OF TSN MECHANISMS

TSN is not limited to scheduled traffic and the TAS. Other traffic classes may have real-time requirements, but cannot be scheduled as the respective streams are not periodic. Different traffic classes may have different sets of real-time requirements, e.g., demanding bounded jitter instead of bounded latency. TSN features more mechanisms which may be applied to fulfill these requirements, such as Asynchronous Traffic Shaping [150] or Cyclic Queuing and Forwarding [18]. A major open problem in TSN is the coexistence of multiple mechanisms and the assignment of

streams to them. Input may be a set of streams or traffic rates with their descriptors and real-time requirements, and output is their assignment to appropriate TSN mechanisms together with the complete network configuration. This problem goes far beyond the TSN scheduling problem, but may impose additional constraints on the latter. Some requirements can only be fulfilled by scheduling the respective streams and computing GCLs for the TAS. Others may not even know the traffic streams in advance and can be implemented by the CBS or even simpler mechanisms. As even computing GCLs for the TAS is a challenging task for current state-of-the-art scheduling and optimization algorithms, such a comprehensive approach is currently unreachable. Hopefully, future works will move towards such long term goals and enable users to exploit the full potential of TSN.

9) UNDERSTANDING OF THE TSN PROBLEM

So far, scalability analyses have been conducted on special algorithms. However, they do not provide insights in what makes the TSN problem hard. This also pertains to all problem extensions like joint routing and multicast, reliability, robustness, BE or ABE traffic, etc. Moreover, properties of schedules such as tightness or average duration of open periods of the TAS have not yet been investigated. It would be helpful to understand the impact of problem extensions on the structure of schedules in an intuitive way. A better understanding of extensions and their impact on schedule structure may facilitate the development of heuristic algorithms that solve larger instances of the TSN problem with acceptable quality compared to exact approaches.

VIII. CONCLUSION

TSN is a set of standards to enable real-time transmission over switched Ethernet networks. IEEE 802.1Qbv [6] defines traffic scheduling combined with the Time-Aware Shaper (TAS), i.e., transmissions of periodic high-priority streams are scheduled such that packets hardly interfere and that ultra-low latency is achieved. Moreover, the TAS protects scheduled traffic against traffic from other traffic classes. This approach requires the configuration of transmission times for streams at the Talkers (source nodes) as well as the configuration of the TAS on the switches.

In this paper, we first gave an introduction to TSN with focus on traffic scheduling and the TAS. We defined the “TSN scheduling problem” and discussed common extensions such as scheduling with fixed or joint routing, various forms of queuing, support for reliability or lower-priority traffic, or respecting technical restrictions. Some of these extensions lead to optimization problems. We summarized frequently used scheduling and optimization methods to tackle these challenges. Then we reviewed a large body of literature about the TSN scheduling problem and classified it regarding the mentioned extensions. Subsequently, we analyzed and compared the works with respect to modelling assumptions, scheduling objectives, problem instances, and scalability, and pointed out advances. We tracked seminal

works and identified popular publication venues for TSN scheduling. We discussed the area by suggesting improvements and pointing out open problems.

This survey serves researchers to identify the current state of the art and open problems in TSN scheduling. The many problem extensions suggest that the construction of an efficient scheduling or optimization algorithm which considers all relevant aspects is infeasible. We expect future work to provide a better understanding of the complexity of the TSN scheduling problem to cover more problem extensions while maintaining scalability.

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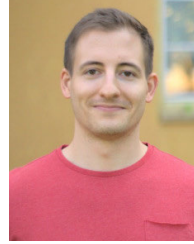
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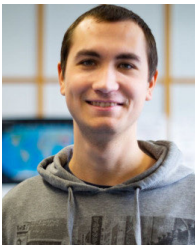
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