Journal of Systems Architecture 138 (2023) 102852

Contents lists available at ScienceDirect

Journal of Systems Architecture

journal homepage: www.elsevier.com/locate/sysarc

A comprehensive systematic review of integration of time sensitive networking and 5G communication

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ARTICLE INFO

Keywords:
Time-sensitive networking
TSN
5G
URLLC
Industry 4.0

ABSTRACT

Many industrial real-time applications in various domains, e.g., automotive, industrial automation, industrial IoT, and industry 4.0, require ultra-low end-to-end network latency, often in the order of 10 milliseconds or less. The IEEE 802.1 time-sensitive networking (TSN) is a set of standards that supports the required low-latency wired communication with ultra-low jitter. The flexibility of such a wired connection can be increased if it is integrated with a mobile wireless network. The fifth generation of cellular networks (5G) is capable of supporting the required levels of network latency with the Ultra-Reliable Low Latency Communication (URLLC) service. To fully utilize the potential of these two technologies (TSN and 5G) in industrial applications, seamless integration of the TSN wired-based network with the 5G wireless-based network is needed. In this article, we provide a comprehensive and well-structured snapshot of the existing research on TSN-5G integration. In this regard, we present the planning, execution, and analysis results of the systematic review. We also identify the trends, technical characteristics, and potential gaps in the state of the art, thus highlighting future research directions in the integration of TSN and 5G communication technologies. We notice that 73% of the primary studies address the time synchronization in the integration of TSN and 5G technologies, introducing approaches with an accuracy starting from the levels of hundred nanoseconds to one microsecond. Majority of primary studies aim at optimizing communication latency in their approach, which is a key quality attribute in automotive and industrial automation applications today.

1. Introduction

There is an urgent need to support ultra-reliable, high-bandwidth, low-latency and predictable communication in many contemporary and future industrial applications [1,2]. Examples of these applications include autonomous driving, autonomous construction sites and mines, collaborating robots, augmented and virtual reality, to mention a few [3–5]. The end-to-end communication in these applications is achieved by combining wired networks (for onboard communication) and wireless networks (for remote communication). The end-to-end (E2E) latency in these applications often ranges from milliseconds for wired onboard communication to microseconds for wireless communication [6,7].

Time-sensitive networking (TSN) is a set of standards for Ethernet-based communication, where the main focus is on providing low-latency and low-jitter for time-sensitive traffic, and even to provide deterministic message transmission over switched Ethernet [6,8–11]. Since it is a wired network, it limits the connection only to the areas where a wired connection is feasible while missing the flexibility of a mobile connection.

The fifth generation of wireless telecommunications (5G) [12,13] can provide the flexibility and scalability required of the mentioned applications. 5G supports real-time applications by using a service called Ultra-Reliable Low Latency Communication (URLLC) which is part of the 3rd Generation Partnership Project (3GPP) Releases [14–17]. URLLC is a promising candidate for real-time wireless communication that can support latency down to 1 ms and reliability up to 99.999% [18–20].

A converged wired and wireless network integrating TSN and 5G is needed to achieve real-time requirements, determinism as well as mobility and scalability of communication in contemporary and future industrial applications. Moreover, the integration of TSN with 5G offers improved Quality of Service (QoS) for time-sensitive applications, such as autonomous driving, industrial automation, and virtual reality. By integrating TSN with 5G, industries will take advantage of the benefits of both technologies to enable new use cases and applications. To

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https://doi.org/10.1016/j.sysarc.2023.102852
Received 27 September 2022; Received in revised form 27 January 2023; Accepted 20 February 2023
Available online 26 February 2023

achieve the E2E QoS requirements of a TSN-5G network a significant effort is required due to the large dissimilarity of the considered systems.

Several core challenges are encountered when integrating the TSN and 5G technologies. Some notable challenges include understanding of the different architectural trade-offs in a joint TSN-5G architecture, time synchronization between the two technologies, simulation, and implementation of a TSN-5G network in a real-world environment, among others. Various initiatives aimed at addressing these challenges. For example, the overview of relevant architecture aspects and the relevant features and processes are described in 3GPP TS 23.501, TS 23.502, TS 23.503, and 5G-ACIA [18]. The interaction between the two technologies is part of 3GPP specifications and there are many research works in this regard. In this paper, we construct a structured map of the existing literature on the integration of TSN and 5G communication technologies. We show that there exist several gaps in the state of the art that require the immediate attention of the community to achieve a seamless integration of TSN and 5G for industrial applications.

1.1. Paper contributions

This Systematic Literature Review (SLR) identifies the research studies conducted in the area of TSN and 5G integration. The main goal of this SLR is to provide a detailed investigation of state of the art on TSN-5G integration and provide a fully-concentrated and well-organized classification scheme introduced in Section 3. This will help the researchers and practitioners in identifying and understanding the existing solutions and their applicability in industrial environments. Another contribution of this SLR is the identification of gaps in the current research and highlighting the opportunities for further research in the area of TSN-5G integration.

In this article, from an initial set of 189 studies, we identified 82 primary studies.[1] We analyzed these studies in detail, following a structured data extraction, analysis, and synthesis process. A summary of the resulting highlights of our study is as follows:

- The efforts in this research area started in 2018, after the initial delivery of 3GPP Release 15 in late 2017.
- 73% of the primary studies address time synchronization between the two technologies, which still represents a significant challenge in the integration of these two technologies.
- In the context of time synchronization between the two technologies, the transparent clock approach is mostly preferred over the boundary clock approach.
- 74% of the primary studies follow an integration architecture, which conforms to the 3GPP releases.
- Majority of primary studies aim at optimizing communication latency in their approach, which is a key quality attribute in automotive and industrial automation applications today.
- Most of the primary studies remain generic without focusing on a specific domain.
- The technical contributions provided by the majority of the existing studies are focused on the integration architecture of TSN and 5G. In this regard, the majority of these studies provide solution proposals or validation research, while missing other types of research such as evaluation research, or experience papers. None of the primary studies have provided a tool as a contribution. This indicates that there is an urgent need for provisioning of tools that incorporate the existing techniques or new techniques for TSN-5G integration.

[1] Primary studies refer to the state of the art publications that are relevant to the goal of this SLR study.

1.2. Paper outline

The rest of the paper is organized as follows. Section 2 describes the research method in detail. Section 3 provides a detailed overview of our data extraction form. Section 4 shows the vertical results of our study, while Section 5 illustrates the horizontal results. Section 6 presents Fleiss Kappa statistical analysis that we used to mitigate threats to validity. In Section 7, we discuss the potential threats to the validity of our study and how we mitigate them. Section 8 presents similar works to our study. Section 9 concludes the paper and presents the future work.

2. Study selection process

This study is conducted and fulfilled based on the well-known guidelines presented in [21,22]. The process is divided into 3 main phases: (i) planning, (ii) conducting, and (iii) documenting as shown in Fig. 1.

Planning. The main objective in the planning phase is to identify the research questions (RQs) and the need for a review of related works and approaches that are performed within the scope of TSN-5G integration. From this phase, a detailed protocol was defined following the specified steps to conduct the study systematically.

Conducting. This phase starts with the search and selection step, where the automatic string search is performed in the four largest databases hosting the research in the domains of computer science, computer engineering, software engineering, and systems engineering, among others. Based on the authors' knowledge of the targeted research domain, three primary studies [23–25] were chosen from the search pool to be considered in the extraction form of the review process. A set of parameters were identified for the classification scheme that was used for the data extraction form of our study. We specified those parameters by systematically applying the standard keywording process [26]. After fulfilling the data extraction form for each of the research studies, we analyzed and synthesized the extracted data to address the research questions (see Section 2.1) posed in this SLR.

Documenting. In this phase, we carried out a detailed analysis of the extracted data. Furthermore, we identified possible threats to the validity of our study. A comprehensive analysis was performed for threat validation and verification. This article was written to document and illustrate the performed study in detail.

2.1. Research goal and questions

The goal of this SLR is:

> "*to classify the technical characteristics as well as to investigate research trends, identify gaps in the state of the art, and highlight open challenges and future directions in the research on integration of TSN and 5G technologies for end-to-end communication in the industrial applications.*"

To achieve this goal, the following research questions are identified based on the authors' knowledge of the research area:

RQ1: *What are the technical characteristics of TSN and 5G integration?*
Objective: to identify and classify existing approaches and techniques for TSN and 5G integration in terms of their technical characteristics.

RQ1.1: *How is resource management conducted in TSN-5G integrated architectures?*
Objective: to classify studies in terms of resource management aspects like configuration model and scheduling.

RQ1.2: *How is the traffic flow managed between TSN and 5G networks?*
Objective: to classify studies related to the different protocols and models they use to manage the traffic flow.

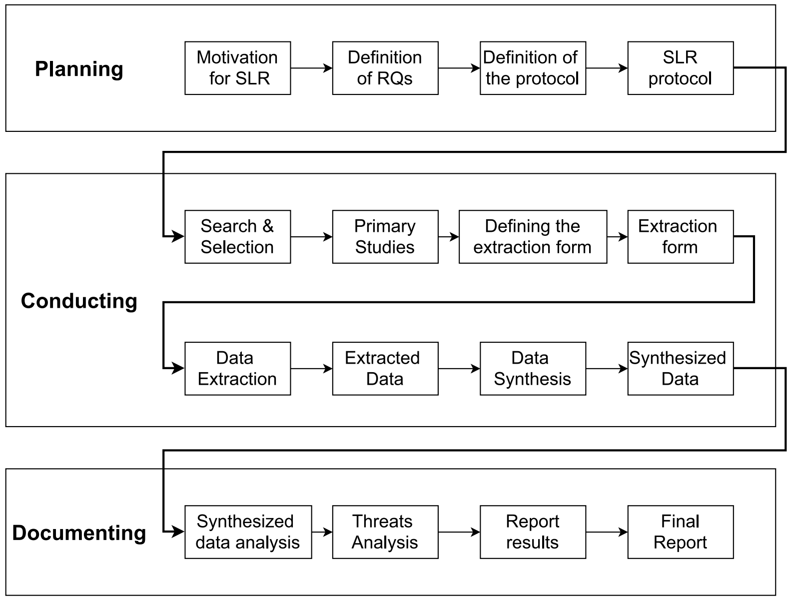

Fig. 1. An overview of the SLR process.

RQ1.3: *Which time synchronization technique is used to achieve a deterministic network environment?*
Objective: to classify the studies in terms of their time synchronization approaches.

RQ1.4: *Which integration architectures are proposed by the research community and what kind of properties do they present?*
Objective: to identify different integration approaches and classify the studies regarding the properties they address.

RQ2: *What are the publication trends of research on TSN and 5G integration?*
Objective: to classify a set of relevant studies in order to assess trends and venues over time.

RQ3: *What are the limitations of TSN-5G integration?*
Objective: to identify current research gaps and limitations with respect to the state of the art research on TSN-5G integration.

The answer to RQ1 will require a detailed investigation of the technical part of this integration, specifically in answering the following questions: (i) what are the different aspects of this integration? (ii) how two different networks can communicate with each other to have a fully converged network? And (iii) what are the core challenges identified in the existing literature. The answer to RQ2 is expected to provide a detailed overview of the current publication trends, research types, and venues. Finally, the answer to RQ3 will assist the research community in understanding whether there is room for improvement in the existing approaches and further research opportunities in this research area.

2.2. Search and selection strategy

After defining the research goal and research questions of our study, we gather the relevant studies available in the research area as presented in Fig. 2.

Before proceeding with the search pool, we first manually select a set of pilot studies based on the authors' knowledge of the targeted area. To select the pilot studies, the authors informally screened the available literature on TSN-5G integration, and selected the followed pilot studies that have a considerable impact on the research area.

1. "5G Industrial Networks With CoMP for URLLC and Time Sensitive Network Architecture" (2019) [23].
2. "Extending Accurate Time Distribution and Timeliness Capabilities Over the Air to Enable Future Wireless Industrial Automation Systems" (2019) [24].
3. "A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing" (2020) [25].

Table 1
Electronic databases and indexing systems considered in this search.

Name	Type	URL
IEEE Xplore Digital Library	Electronic database	www.ieeexplore.ieee.org
ACM Digital Library	Electronic database	www.dl.acm.org
SCOPUS	Indexing system	www.scopus.com
Web of Science	Indexing system	www.webofknowledge.com

We use these works to formulate the search string and to identify some of the parameters of our data extraction form. Moreover, we perform a manual search in the so-called grey literature (e.g., web pages, forums, etc.) on the Google search engine, to identify any white paper that provides relevant information for our study. Two parallel activities were carried out: the *review of the peer-reviewed literature*, and the *review of the grey literature*.

2.2.1. Automatic search

To identify the relevant studies, we conduct an automatic search on four of the largest and most complete databases in computer science, computer engineering, software engineering, and systems engineering: IEEE Xplore Digital Library, ACM Digital Library, Scopus, and Web of Science as shown in Table 1. The selection of these electronic databases and indexing systems was motivated by their high accessibility and the fact that they export search results to well-defined and computation-amenable formats. Furthermore, one of the strongest points is the fact that these databases are recognized as being effective means to conduct systematic literature reviews [27].

We define the search string based on the keywords extracted from the research questions and the pilot studies. We use the same search string in all databases and the process we adapted is based on the search fields required by the digital libraries: title, abstract, and keywords. Our search string is as follows:

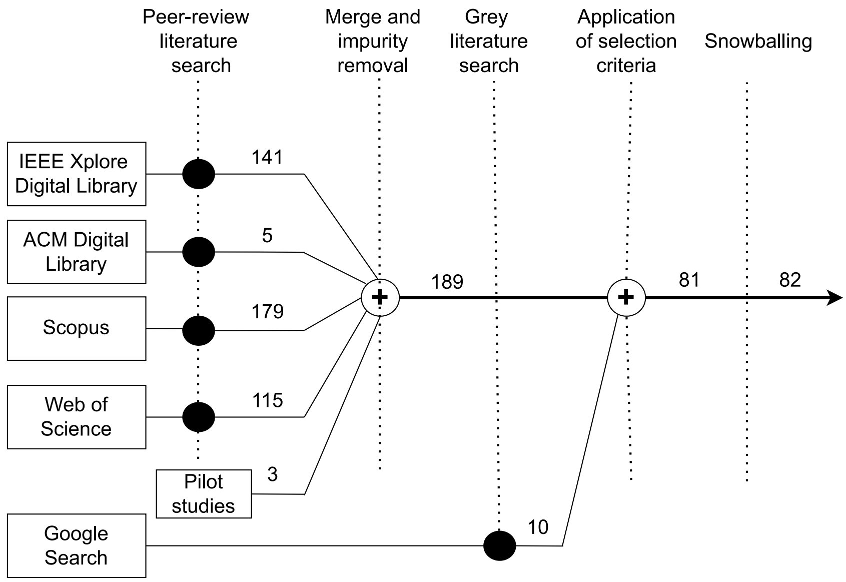

Fig. 2. Search and selection process.

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(("Time Sensitive Network*" OR "Time-Sensitive Network*" OR
 "Time Sensitive Communication" OR "TSN") AND (("5G" OR
 "URLLC") OR (("5G")
 AND ("Virtual bridge" OR "Transparent Bridge"
 OR "ULL"))))
```

The search results include 141 publications in IEEE Xplore Digital Library, 5 in ACM Digital Library, 179 in Scopus, and 115 in Web of Science.

2.2.2. Impurity and duplicates removal

Since some of the research studies can be indexed in more than one database, we first removed the duplicates. Then we addressed impurities in our searches such as abstracts and tutorials. We performed this process by using a tool called StArt [28] that supports the SLR process. After removing the duplicates, we achieved 189 publications – see Fig. 2.

2.2.3. Grey literature search

To collect the grey literature, we follow the guidelines for including grey literature and conducting multivocal literature reviews in software engineering [29]. According to these guidelines we target Google Search Engine, performing the automatic search with the same string search as before, and a manual search based on our knowledge of the targeted research area. The grey literature gave us 10 more primary studies as in Fig. 2.

2.2.4. Application of selection criteria

In the next step, we apply our inclusion and exclusion criteria to all the publications to identify the primary studies that correspond to the relevant publications for this study. In this step, we classify each publication as "Relevant", "Non-Relevant" and "Not Clear". We perform this classification by reviewing the title, abstract, and keywords of each publication. The publication is considered relevant if it addresses the goal and purpose of this study. If the publication is out of the scope of this study, then it is considered non-relevant. Otherwise, if we cannot classify the publication as relevant or non-relevant based on the abstract, title, and keywords, it is set as not clear. In this case, we perform full-text skimming of the publication with the aim of classifying it as relevant or non-relevant. The selection criteria are as follows.

Inclusion criteria for Peer-reviewed literature

(ICP1) The research study addresses the integration of TSN and 5G.
(ICP2) The research study is written in English.
(ICP3) The research study is a peer-reviewed publication, i.e., published in a peer-reviewed journal, workshop, conference, or book.
(ICP4) The research study is available as full-text.

Inclusion criteria for Grey literature

(ICG1) Web page or white paper reporting on an integration technique/framework/architecture for TSN and 5G.
(ICG2) Web page or white paper reporting on a formalization and/or implementation of the proposed TSN and 5G integration approach.
(ICG3) Web page or white paper is in English.
(ICG4) Web page or white paper is freely accessible.

Exclusion criteria for Peer-reviewed literature

(ECP1) Secondary and tertiary studies such as systematic literature reviews, surveys, etc.
(ECP2) Studies in the form of tutorial papers, short papers, editorials, manual, or poster papers because these types of publications do not provide enough information to answer the posed questions.

Exclusion criteria for Grey literature

(ECG1) Web page or white paper that does not clearly discuss integration of TSN and 5G.
(ECG2) Videos, webinars, books, etc. since they are too time-consuming to be considered for this study.

Even though the secondary/tertiary and other studies are excluded from the search pool, we consider them in identifying any important issues to be considered in our study and for providing a summary of what is already known on TSN-5G integration.

After removing the duplicates and applying the inclusion/exclusion criteria to both the peer-reviewed literature and the grey literature, we managed to get a set of 81 primary studies. The majority of primary studies were excluded due to the removal of impurities and duplicates (251 studies). 91 primary studies were excluded due to not addressing the goal and purpose of this study (not fulfilling ICP1). Moreover, 1 primary study was excluded as it was not written in English (not fulfilling ICP2), and 8 primary studies were excluded as they were not available as full text (not fulfilling ICP4). In addition, 33 primary

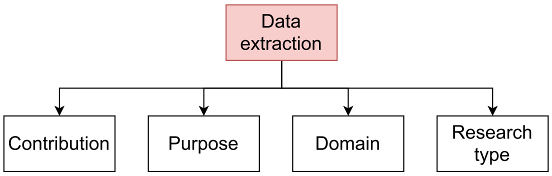


Fig. 3. The top-level categories in the data extraction form.

studies were excluded due to being secondary and tertiary studies (ECP1), and 6 primary studies were excluded due to being editorial papers, or posters (ECP2). Note that some of the studies were excluded as they did not fulfill (or fulfilled) more then 1 inclusion (exclusion) criteria.

2.2.5. Snowballing

To mitigate any potential bias regarding the construct validity of our study, we perform a closed recursive backward and forward snowballing activity[2] [30]. The starting set of our search is the set of primary studies presented earlier and the pool of selected studies after the second string search as shown in Fig. 2. From the recursive backward and forward snowballing, we found two more relevant studies. The full text of one of these studies is not available which violates the inclusion criteria ICG4. Therefore, we remove this study and add the remaining study to the pool of primary studies, which makes the total number of primary studies equal to 82.

The number of relevant studies is low as we expected because the targeted research area is still in its infancy. Note that the integration of TSN and 5G technologies is discussed for the first time in the specification of 5G in 2018. Thus, the research on the integration of TSN and 5G technologies has not gained maturity.

3. Data extraction

In this phase, we create a data extraction form (classification form) that is used to extract the required data from the primary studies. We follow a systematic process based on keywording for defining the parameters in the top levels of the data extraction form in Fig. 3. Furthermore, we use keywording to extract data from the primary studies accordingly.

The goal of the keywording is to effectively develop an extraction form that can fit existing studies while taking their characteristics into account [26]. We collect the keywords and concepts by studying the full text in the primary studies. After collecting the keywords and concepts, we perform a clustering operation to organize them according to the identified categories. The clustering operation is similar to the sorting phase of the grounded theory methodology [31]. During this phase, we collect any additional information that was marked relevant but did not fit within the data extraction form. We refine the data extraction form after the revision of the collected additional information if needed. The previously analyzed primary studies are re-analyzed according to the refined data extraction form. The process is completed only when all the primary studies are analyzed. The final set of analyzed primary studies includes 82 publications.[3] We provide a detailed overview of the data extraction form in the following subsections.

[2] Backward snowballing refers to scouring the references sections of papers that are already included in the review, while forward snowballing refers to tracking articles that had subsequently cited any of the papers included in the review.

[3] The final set of primary studies corresponds to studies published until **January 21, 2023**, which corresponds to the last day of our search.

3.1. Contribution

This top-level category captures the research contributions concerning TSN-5G integration in the primary studies. Fig. 4 depicts the internal hierarchy of the research contribution category. It consists of three sub-categories: (i) technical contribution, (ii) contribution type, and (iii) maturity level of the contribution. These categories are described as follows.

3.1.1. Technical contribution

This category describes what technical contribution is provided by a primary study. It can be further classified into resource management, flow management, time synchronization, and integration architecture.

The resource management category refers to how the TSN-5G integrated system's resources, including configuration models and scheduling are managed in a primary study [32]. Note that we focus on the data extraction corresponding to the resource management in integrated TSN and 5G networks. We categorize the configuration models according to the IEEE 802.1QCC (2018) [33] as follows:

- *Fully Distributed model:* All the end stations communicate their requirements directly using the Stream Reservation Protocol (SRP) [33]. SRP is a standard that provides mechanisms to reserve bandwidth per queue on the path of a frame. In SRP, a sender can request a reservation for a certain amount of bandwidth in order to transmit a data stream. The reservation request is sent to a reservation server, which determines whether the requested amount of bandwidth is available and, if yes, it allocates it to the sender. The sender can then transmit the data stream using the reserved bandwidth part. Some potential research directions on SRP may be security enhancement, scalability, integration with other protocols, etc.
- *Centralized network/distributed user model:* There exists a centralized entity called Centralized Network Configuration (CNC) that gathers the information about bridge (TSN switch) capabilities and uses a remote management protocol to perform functions like scheduling, resource reservation and other types of configuration.
- *Fully Centralized model:* This model contains, in addition to the CNC, an entity called the Centralized User Configuration (CUC) that collects all user requirements and interacts with the CNC to decide the topology and scheduling of the network.

The flow management category refers to data models or protocols that enables users or operators to dynamically discover, configure, monitor, and report the bridge and end station capabilities [7]. Among several models and languages, the prominent one in the context of TSN and 5G is the YANG model that is used to model configuration data, state data, Remote Procedure Calls (RPCs), and notifications for network management protocols [34]. The YANG model is a formal contract language used for networking, and widely adopted in industries. This is the main motivation why the TSN Task Group decided to establish IEEE 802.1QCP standard to support YANG data modeling. The YANG model is used by the widely accepted protocols, such as NETCONF and RESTCONF, to simplify network configuration, as described below.

- NETCONF is a network management protocol which provides mechanisms to install, manipulate, and delete the configuration of network devices [35]. It is used by the centralized entity of a TSN configuration model (CNC) to configure the switches following a client–server model [36].
- RESTCONF is a network management protocol used to provide the Create, Read, Update, Delete (CRUD) operations on a conceptual data store containing YANG-defined data [37]. It provides an interface to NETCONF data stores leveraging the HTTP methods. In the fully centralized TSN configuration model, it appears as an interface between the CNC and CUC entities.

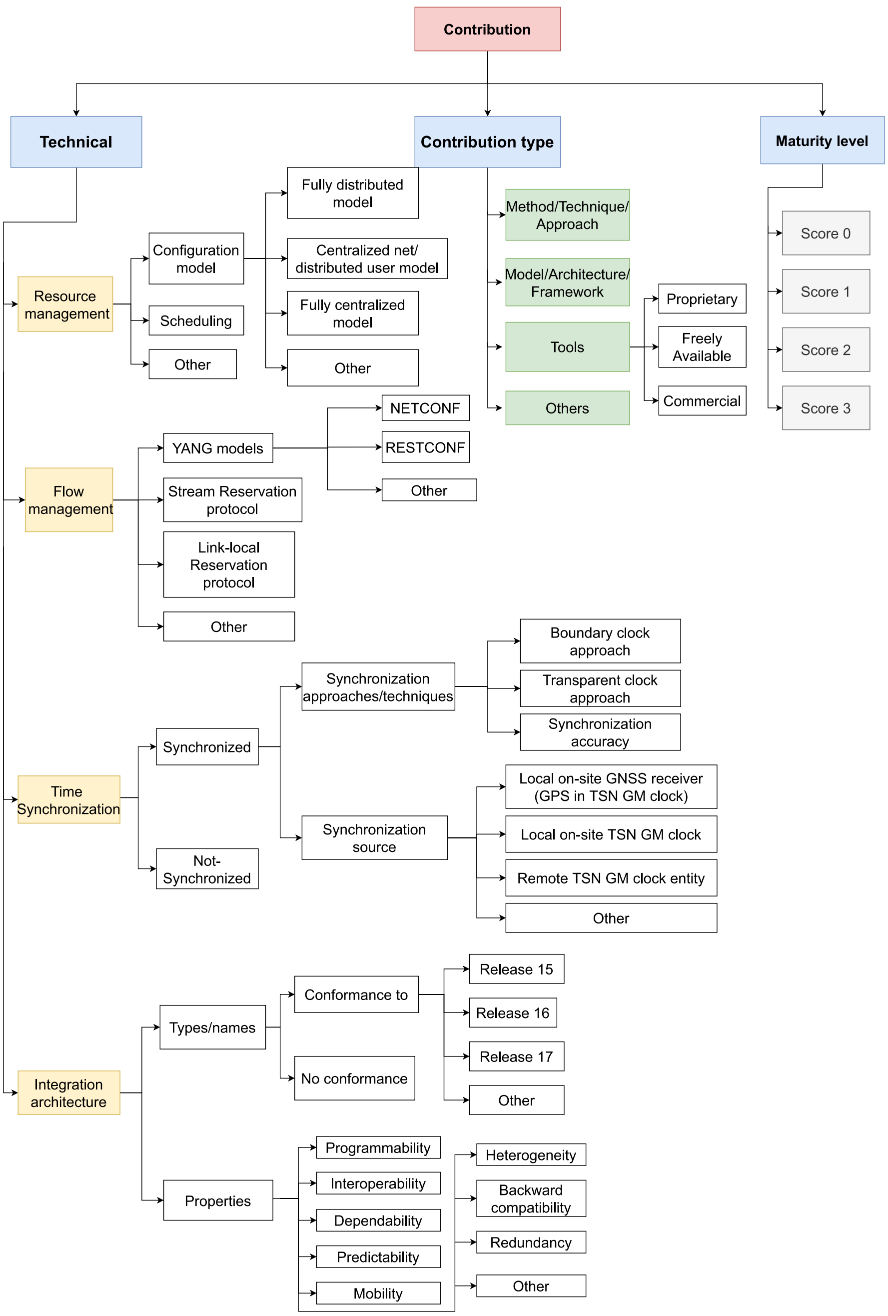


Fig. 4. Data extraction, considering all the main topics in terms of technical issues, types of contributions, and maturity level.

In addition to the above well-known models, Stream Reservation Protocol (SRP) [33] and Link-Local Reservation Protocol (LLRP) [38] are the flow management protocols used solely in TSN and wireless networks, respectively. They help in improving the performance and reliability of the network by ensuring necessary resources to critical devices and traffic.

Time synchronization category refers to the synchronization of TSN and 5G to achieve a whole unified and converged network. Synchronization may vary depending on the time synchronization approach and/or the source of synchronization. We also consider the studies that do not address the time synchronization approach. We categorize time synchronization approaches according to TR 23.734 [39] as follows:

- *Boundary clock approach:* The 5G Radio Access Network (RAN) has a direct connection to the TSN master clock and the timing information is provided to User Equipment (UE) via the 5G broadcast channels.
- *Transparent clock approach:* This approach uses the generalized Precision Time Protocol (PTP) [40] messages to achieve synchronization. The gPTP is a network protocol used to synchronize the distributed clocks within a communication network. The synchronization of clocks between network devices is achieved by passing relevant time event messages [41].

Even though the 3GPP working group addresses synchronization accuracy in the range of hundreds of nanoseconds, this accuracy still depends on the suggested approach.

The integration architecture category refers to the proposed TSN-5G architecture. This architecture can either conform or not conform to the 3GPP Releases. In the latter case, the architecture is often designed according to the authors' knowledge of the targeted area. Most of the works follow the 3GPP Releases, which are developed in a backward compatible manner by the 3GPP working group. Release 17 is still under development but there are several researchers that already refer to this release in their works.

In addition, there are different properties of the architectures that can be addressed. We identify the following core properties:

- *Programmability:* using different algorithms to dynamically reprogram the nodes. The current effort on network programmability is mostly centered around the separation of the data and control planes [42,43].
- *Interoperability:* different networks can communicate easily without the need for additional tools or interfaces. This concept is not only related to communication but also to the specification and implementation of an application [44]. Interoperability can be categorized with respect to the resources, protocols, services, and timeliness of the communication. Further definitions of interoperability are presented in [45,46].
- *Dependability:* the ability of a system to provide services that can be trusted within a time period. It includes the system's availability, reliability, maintainability, maintenance support, and performance and in some cases, it may include durability, safety and security [47,48].
- *Predictability:* is related to proving, demonstrating, or verifying the fulfillment of the system's timing requirements. In the artificial intelligence community, predictability is also related to the support for mechanisms that predict beforehand the future state of the system [49,50].
- *Mobility:* refers to network mobility. Based on some measurement reports, the network may possibly move (i.e., handover [51]) the mobile terminal connection from the serving cell to that neighbor cell, so the mobile terminal will get better radio conditions [52].
- *Heterogeneity:* in the sense of a network containing different types of nodes as in [53]. Software, hardware, and technology variation between mobile devices cause heterogeneity [54].
- *Backward compatibility:* is the ability of a network to be compatible with earlier versions, meaning that all the previous features will be valid in the new version [55]. For example, 5G devices are able to operate on earlier-generation networks (4G, 3G, etc.).
- *Redundancy:* is the duplication of network instances such as devices or lines of communication to increase the system's reliability and to reduce the risk of failures. It is one of the mechanisms to provide reliable data transfers [56,57].

3.1.2. Contribution type

Another sub-category of the contribution is the contribution type. It consists of (i) method, technique, or approach, (ii) model, architecture, or framework, and (iii) tool. A tool can be:

- *Proprietary:* A tool that is not commercially available but there is a party that has the right to grant a license for using it.
- *Freely available:* Open for all users.
- *Commercial:* This tool has a commercial purpose but licence might be needed in order to use it or it can be open-source depending on developers' decision.

3.1.3. Maturity level

Maturity level of a study is described based on maturity classification according to the Redwine–Riddle maturity model [58]. Accordingly, Score 1 means "not mature at all", so the study only presents the basic ideas but there is no proof of concept. Score 2 means "somewhat mature", the study provides a proof of concept, and the contribution is also demonstrated on use cases. The highest is a score 3, which means "mature", the study includes the proof of concept and the usability presented on one or more use cases. Furthermore, there is evidence of the usage of the contribution by the research community. Score 0 means "inconclusive", the contribution of the study cannot be classified as any of the above ones.

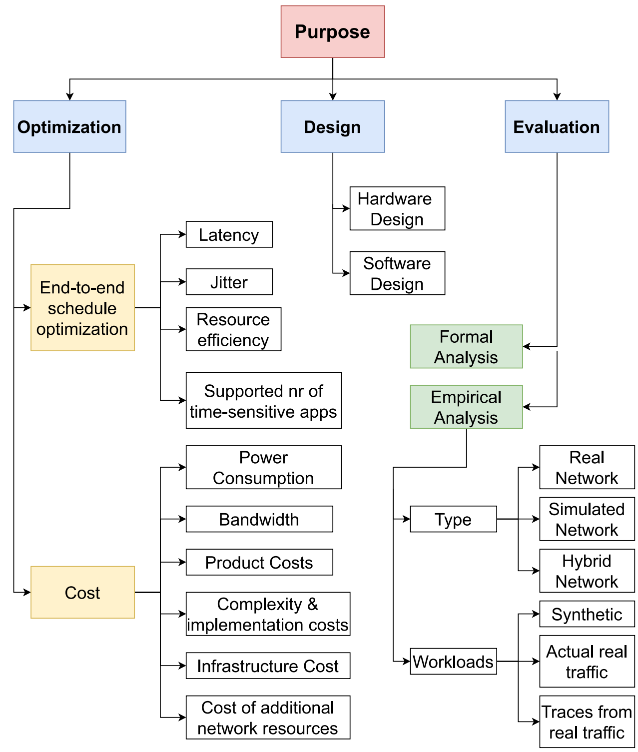


Fig. 5. Data extraction form, considering different purposes of each primary study.

3.2. Purpose

The second top-level category in the data extraction form is denoted by "purpose". This category classifies the primary studies according to the purpose of the contribution. We identify three main purposes of the contributions in the area: (i) to **optimize** specific aspects of a technique, (ii) to **design** a new technique or an architecture, and (iii) to **evaluate** a current technique or architecture as depicted in Fig. 5.

3.2.1. Optimization

The optimization refers to the end-to-end schedule optimization [59] or cost optimization. End-to-end schedule optimization considers the following parameters:

- *Latency:* measures the time it takes for data to propagate from its source node to its destination node via the network.
- *Jitter:* a variation in delay usually caused by network congestion.
- *Resource efficiency:* addressed in some of the primary studies which aim to achieve an improved schedule of the network.
- *Supported number of time-sensitive applications:* affects the timing requirements and overall performance of the network.

Cost is a broad aspect of optimization, which can be further categorized as follows:

- Power Consumption
- Bandwidth
- Product Costs

- Complexity and implementation costs
- Infrastructure cost
- Cost of additional network resources

3.2.2. Design

The purpose of a primary study could be to develop a technique or a method for designing an architecture or a prototype of a TSN-5G integrated system. The designed prototype could represent, for example, a hardware and/or software for the network interface that supports connectivity, synchronization, scheduling, and analysis of TSN-5G integration.

3.2.3. Evaluation

The purpose of a primary study could also be to evaluate a technique or a method for TSN-5G integration using formal and/or empirical analysis. The analysis can be performed on a real network, simulated network, or hybrid network. Furthermore, the workloads used for the evaluation could be (i) synthetically generated, (ii) acquired from real network traffic, or (iii) based on the traces generated by running real traffic.

3.3. Domain

The third top-level category in the data extraction represents the application domain of the research contribution presented in each primary study. The proposed contribution in a primary study could be applicable generally or proposed for a specific domain or a particular segment of the industry, e.g., industrial automation [60,61], automotive [62–64], railways, avionics, etc.

3.4. Research type

The general taxonomy of classifying research studies based on their research type is summarized in [65]. To classify the research type in the primary studies, we use a reduced classification of the general taxonomy as presented in [66]. We classify the primary studies using the following research types.

I. *Solution Proposal* - This type of research proposes a new technique or an extension of an existing technique and discusses its relevance. Small examples, a sound argument or other means may be used to provide a proof of concept of the proposed/extended technique.
II. *Validation Research* - This type of research aims at investigating some properties of a solution proposal and presenting a novel technique or method that is not yet implemented in practice. The investigation is conducted systematically utilizing various activities, including the development of prototypes, performing simulations, conducting experiments, performing mathematical analysis, and mathematically proving the properties.
III. *Conceptual (Philosophical) Proposal* - This type of research proposes a new conceptual framework. Furthermore, using the framework provides a new way of looking at the problem at hand.
IV. *Evaluation research* - This type of research evaluates an implemented solution in practice (real environment). The evaluation is often conducted by means of case studies, field studies, or field experiments.
V. *Experience paper* - This type of research presents the lessons learned by the researchers from their own experience of solving the research problem. These kinds of studies are performed by researchers who have used some tools in practice or by industry practitioners who report their experience of studying the problem in industrial settings.

Table 2
Categorization and tabulation of primary studies based on the technical contributions.

Technical category	Reference to the paper
Resource management	[23–25,60–62,68–111]
Flow management	[23,24,60,61,68–71,73–76,78,79,81–85,96,98,99,107,108,110,112–114]
Time synchronization	[23–25,61,62,68–71,74–76,78,79,81,83–85,87–91,93,94,97,98,100,102,104–108,111–113,115–137]
Integration architecture	[23–25,60–62,68–143]

4. Results: Vertical analysis

We follow the data analysis guidelines provided by Cruzes and Dyba [67] to perform the vertical and horizontal analyses of the extracted data that we gathered in this study. The vertical analysis, performed in this section, is used to find information about each of the categories identified in the data extraction form. As the first step, we analyze each primary study specifying the parameters that the extraction form requests, and then we analyze the entire pool of primary studies to find any potential gap in the existing research. Note that we also provide summary tables (Tables 2–13) where each primary study is connected to each specific category and its characterizing value(s). The references underlined are common between two different categories.

On the other hand, horizontal analysis (presented in the next section) is used to identify the possible relations between two different categories, showing the trends and potential gaps through contingency tables.

This section provides an analysis of each of the categories of our data extraction form and answers our first and second research questions. We access trends and venues of primary studies over time. Furthermore, we investigate the existing approaches and techniques for TSN-5G integration in terms of their technical characteristics. The selected set of primary studies is presented in Table 2. This table categorizes the primary studies based on the technical contributions specified in Fig. 4. We choose this special category as it includes all the set of primary studies considering our goal to focus particularly on TSN-5G integration.

In the following subsections, we provide an answer to our first research question: *RQ1: What are the technical characteristics of TSN and 5G integration?*

4.1. Analysis based on technical contributions

In this subsection, we investigate the set of primary studies based on their technical contributions to the research area. Based on our classification scheme, we analyze the technical contributions of the studies based on the aspects they address, which can be resource management, flow management, time synchronization, and integration architecture, as shown in Fig. 6. A summary table of the primary studies belonging to each technical category was presented earlier in Table 2.

We notice that 73% of the primary studies address the time synchronization, which is actually a significant challenge for the integration of TSN and 5G technologies. 60 primary studies focus on time synchronization of TSN and 5G. The majority of the primary studies propose a synchronized approach with an accuracy starting from the levels of hundred nanoseconds to one microsecond. There are six primary studies [81,85,87,98,103,121] that do not consider time synchronization, but rather propose non-synchronized solutions for TSN and 5G integration. Usually, the choice of synchronized or non-synchronized solution depends on the specific requirements of the system. Clock synchronization is a critical aspect in real-time systems, where the timing of events and the order in which they occur can have significant consequences.

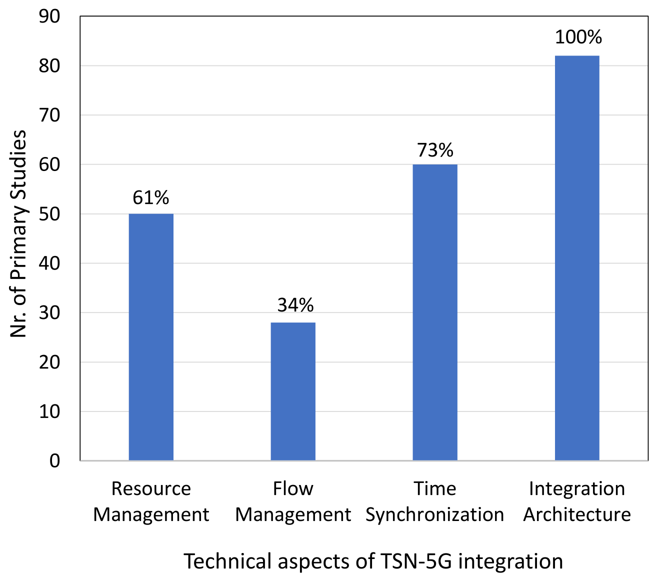


Fig. 6. Number of primary studies providing various technical contributions for TSN-5G integration.

Table 3
A summary of primary studies according to the approach they use to achieve the time synchronization.

Time synchronization approach	Reference to the paper
Transparent clock approach	[24,25,62,71,79,83,88,91,93,94,97,100,102,104,106,111,113,115–118,120,122–124,126–129,131–133,135,137]
Boundary clock approach	[23,125]

The majority of the primary studies (34) that address time-synchronization use the transparent clock approach that utilizes the Precision Time Protocol (PTP). Whereas, there are only two primary studies that use the boundary approach as shown in Table 3.

The transparent clock approach is usually used in high-precision applications, to maintain a very accurate view of the current time because it takes into account the delays introduced by the network itself. On the other hand, the boundary clock approach is simpler to implement and maintain, but it is less accurate as it depends on the accuracy of the clocks at the boundary of each subnetwork, which may not be as precise as more central clocks. Note that both approaches are proposed by the 3GPP standards.

There are 50 primary studies (61% of the total) that provide technical contributions in the context of resource management in TSN-5G integrated systems. Among these studies, 31 use the fully centralized configuration model proposed by the IEEE 802.1 QCC standard (Table 4). One advantage of the centralized model compared to the distributed one is that the centralized model can be easily incorporated into the specifications provided by 3GPP to manage and control the TSN-5G network.

On the other hand 23 primary studies focus on providing different scheduling techniques for TSN-5G network. Among the scheduling algorithms semi-persistent scheduling (SPS) is used by the majority of the papers, as shown in Table 5. In SPS, a dedicated channel is reserved for a specific user for a predetermined period of time. SPS is a useful technique for supporting the transmission of periodic data with low latency and high reliability in wireless communication systems, however it may not be suitable for traffic that is highly variable or unpredictable in nature, as it may require a more flexible scheduling approach.

Table 4
A summary of primary studies according to the network configuration model.

Configuration model	Reference to the paper
Fully distributed model	[25]
Centralized network/distributed user model	[23]
Fully centralized model	[24,25,60–62,68,71,72,74,76,78–83,86,88,89,91–93,96,100,101,103,106–109,111]
Others	[69,73,85]

Table 5
A summary of primary studies according to the proposed scheduling technique.

Scheduling technique	Reference to the paper
Semi-persistent scheduling	[23,24,60,76,77,99,100]
Configured grant scheduling	[60,71,100]
Dynamic scheduling	[68]
Window-based scheduling	[86]
Others	[61,72,74,75,84,85,95,102,106,108–111,118]

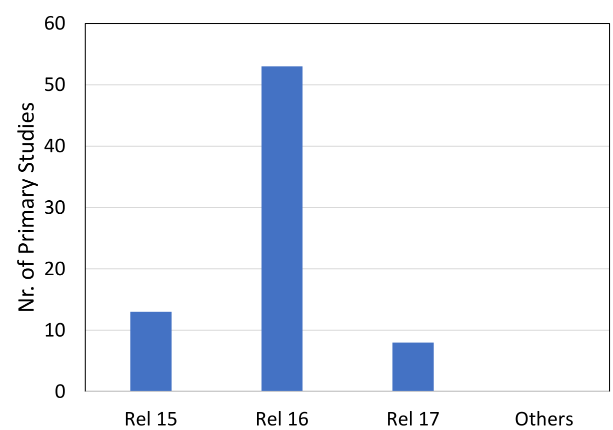


Fig. 7. Number of primary studies conforming to various releases of the 3GPP specification.

The analysis of the primary studies also reveals that 74% of these studies (representing % of all studies) contribute towards the integration architectures for TSN and 5G that conform to the 3GPP specifications (Release 15, 16, 17 or others as shown in Fig. 7). Whereas, the TSN-5G integration architectures addressed in the remaining primary studies (26% of the total number of primary studies) do not comply with any of the 3GPP Releases [68–70,72,80,84,85,95–99,110,121,124,130,132–134,136,142].

In addition, the number of primary studies addressing each property of the TSN-5G integration architecture is depicted in Fig. 8, while a summary table of the primary studies belonging to each integration architecture property is presented in Table 6. Overall, dependability is an essential requirements for TSN-5G network as it enables the transmission of time-critical data with low latency and high reliability. TSN networks need to be secure in order to prevent unauthorized access to the critical data. Ensuring the security of TSN in a 5G environment is one of the major challenges, as it requires the integration of multiple security technologies. On the other hand, interoperability is also a challenge, as TSN and 5G components may use different protocols and technologies. It should be noted that one of the challenges of TSN-5G integration comes from the standardization. TSN is still an evolving standard, and this can lead to challenges in terms of interoperability and compatibility as there might be ongoing efforts to standardize TSN-5G integration.

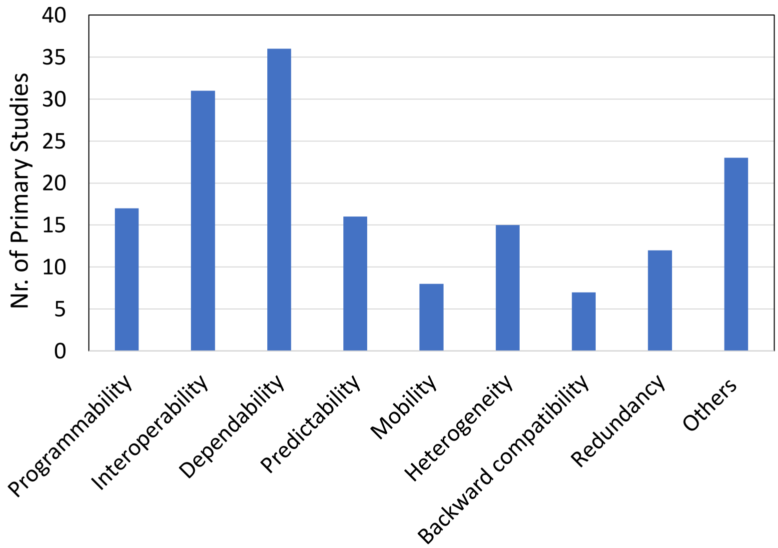


Fig. 8. Number of primary studies addressing various properties of integration architectures for TSN and 5G.

Table 6
A summary of primary studies according to the properties of integration architectures for TSN and 5G. Note that the references underlined are common between two different categories.

Architecture's properties	Reference to the paper
Programmability	[24], [60], [61], [68], [69], [72], [73], [85], [86], [87], [92], [98], [103], [132], [110], [108], [136]
Interoperability	[23], [24], [60], [61], [68], [72], [74], [81], [82], [83], [88], [89], [92], [95], [96], [100], [101], [102], [103], [104], [119], [120], [121], [138], [141], [106], [114], [107], [108], [111], [142],
Dependability	[23], [61], [68], [76], [81], [82], [83], [84], [86], [89], [90], [91], [93], [96], [98], [99], [100], [102], [112], [118], [120], [128], [129], [131], [132], [133], [138], [139], [140], [106], [134], [109], [110], [135], [143]
Predictability	[23], [24], [60], [61], [69], [76], [80], [102], [115], [116], [117], [122], [139], [108], [136], [137]
Mobility	[24], [70], [62], [76], [78], [79], [113], [139]
Heterogeneity	[68], [70], [72], [73], [74], [82], [85], [84], [92], [99], [101], [105], [139], [114], [108]
Backward compatibility	[82], [87], [88], [93], [103], [116], [121]
Redundancy	[23], [24], [25], [61], [68], [71], [78], [81], [84], [118], [119], [134],
Others	[25], [75], [77], [81], [91], [93], [94], [97], [98], [99], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [141], [135]

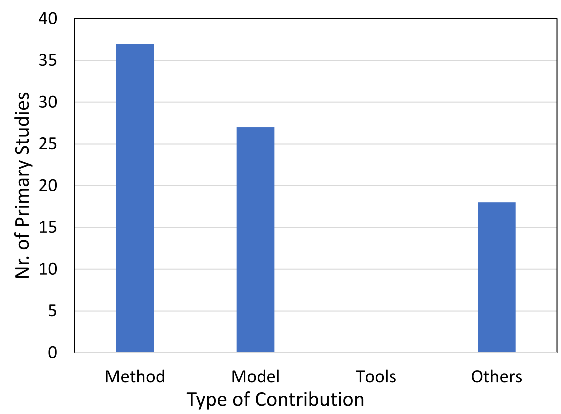


Fig. 9. Number of primary studies providing the type of contribution with regards to TSN-5G integration.

Table 7
A summary of primary studies according to the type of contribution with regard to TSN-5G integration.

Type of contribution	Reference to the paper
Method	[25,62,71,73,74,80,85,86,92–94,97,100,101,103,104,109,110,112,114–118,120–124,126–128,130,135,137,140,142]
Model	[23,60,68–70,72,76,78,79,81,82,84,91,95,96,98,99,102,108,113,119,125,132,133,136,138,143]
Tool	–
Others	[24,61,75,77,83,87–90,105–107,111,129,131,134,139,141]

4.2. Analysis based on the contribution type

In this subsection, we discuss the distribution of the primary studies considering their type of contribution as presented earlier in Section 3.1.2. Fig. 9 presents the number of primary studies addressing each contribution type. It can be observed that 37 primary studies focus on providing a method, technique, or approach for TSN-5G integration. Similarly, a set of 27 primary studies provide a model, architecture, or framework for TSN-5G integration.

It is interesting to note that none of the primary studies have provided a tool as a contribution (Table 7). Often, tools are the means to transfer scientific results to the industry. This indicates that there is an urgent need for provisioning of tools that incorporate the existing techniques or new techniques for TSN-5G integration. The remaining 18 primary studies provide other contributions, e.g., to provide options for TSN and 5G, to investigate the impact and derive requirements on the end-to-end system, to present the key technologies, challenges, and research directions.

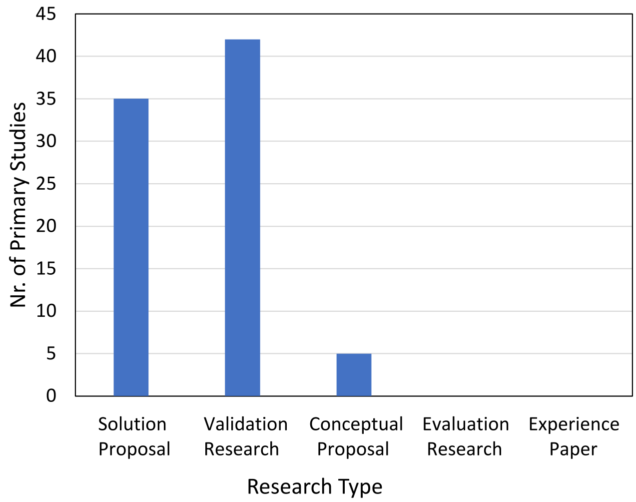


Fig. 10. Distribution of primary studies according to research type classification.

Table 8
A summary of primary studies according to research type classification.

Research type	Reference to the paper
Solution proposal	[24,25,60,62,68,70–73,75,76,79,83,88–90,93,94,96,100,106,108,112,116,120,121,124,129,130,135,136,138,139,143]
Validation research	[23,61,69,74,77,78,80–82,84–87,92,95,97–99,101–104,109–111,113,115,117–119,122,123,125–128,132–134,137,140,142]
Conceptual proposal	[91,105,107,131,141]
Evaluation research	–
Experience paper	–

4.3. Analysis based on the research type

There are 5 research types that we presented as part of the data extraction form: (i) solution proposal, (ii) validation research, (iii) conceptual (philosophical) proposal, (iv) evaluation research, and (v) experience paper. We identify that 42 primary studies provide validation research for TSN-5G integration. Similarly, 35 primary studies present solution proposals for the integration of TSN and 5G as shown in Fig. 10. These studies develop proof-of-concept prototypes and perform simulations and mathematical analysis using the prototypes. Only 5 primary studies provide conceptual proposal for TSN-5G integration. It is interesting to note that none of the primary studies provide evaluation research or experience papers (Table 8). This analysis identifies a gap in the research types in this area, which is also an indicator of the immature nature of TSN-5G research.

4.4. Analysis based on the maturity level

In this subsection, we analyze the primary studies with respect to the maturity levels according to the Redwine–Riddle maturity model [58], also described in Section 3.1.3. According to this model, we classify the primary studies using one of the scores: 0, 1, 2, or 3 representing "inconclusive", "not mature at all", "somewhat mature" or "mature" respectively. It can be observed in Fig. 11 that 55% of all primary studies are somewhat mature as the technical contributions in these studies have been demonstrated in use cases involving TSN-5G integration. Whereas, 43% of all primary studies are not mature at all as they only present basic ideas without providing any proof of concept for TSN-5G integration. It is interesting to note that only two of the primary studies are mature according to the Redwine–Riddle maturity model.

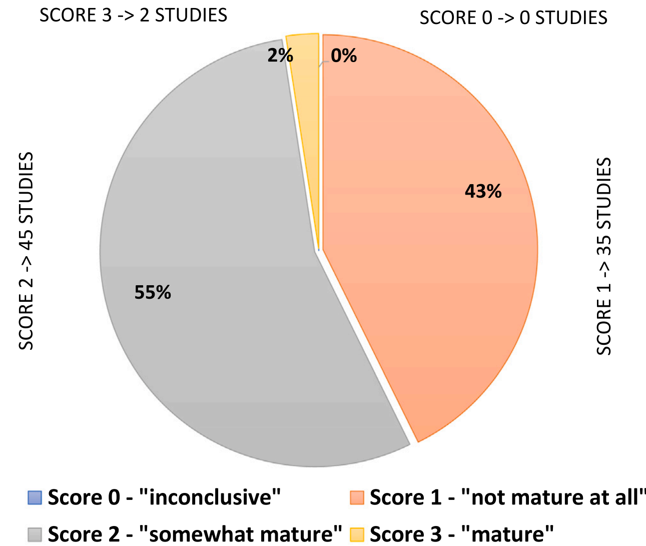


Fig. 11. Distribution of primary studies according to the maturity level of their contributions with regard to TSN-5G integration.

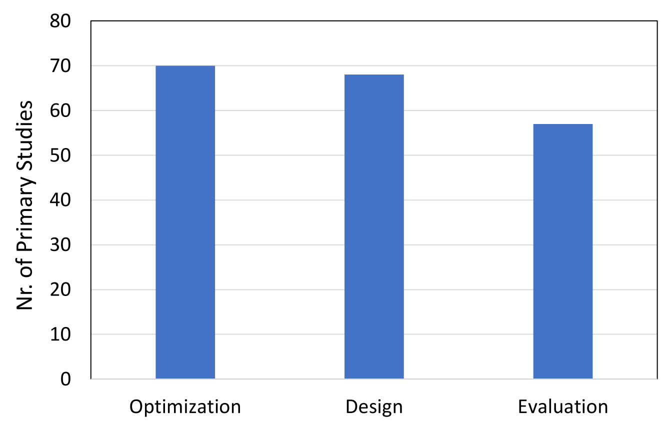


Fig. 12. Number of primary studies according to the purpose of contribution in the context of TSN-5G integration.

4.5. Analysis based on the purpose of contributions

In this subsection, we analyze each primary study based on the purpose of the contribution as discussed in Section 3.2. Fig. 12 presents the number of primary studies that aim at evaluating, designing, or optimizing some techniques for TSN and 5G integration. We notice that a large majority of the primary studies (70) focus on optimizing the TSN-5G integrated systems. Furthermore, 68 primary studies focus on design, whereas 57 primary studies provide an evaluation of the techniques for TSN-5G systems. Note that several primary studies have more than one purpose in the proposed contributions, e.g., to design and evaluate, to design and optimize, or to optimize and evaluate.

4.5.1. Purpose of contribution – optimization

If the purpose of contribution in a primary study is to perform optimization, then we identified two sub-categories in our data-extraction form: end-to-end schedule optimization and cost optimization. Fig. 13 shows that 74% of the primary studies aim at optimizing latency, which is a key quality-of-service attribute in many applications in various domains, e.g., Industrial Internet of Things (IIoT). Achieving TSN low latencies in a 5G network may be challenging due to the high traffic volumes and potential interference from other devices.

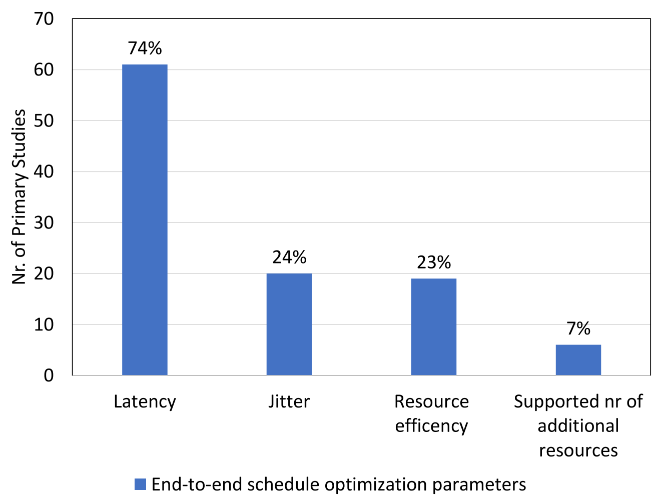


Fig. 13. Number of primary studies addressing various attributes for end-to-end schedule optimization in TSN-5G systems.

Table 9
A summary of primary studies according to various attributes for end-to-end schedule optimization in TSN-5G systems.

Scheduling parameter	Reference to the paper
Latency	[23], [24], [60], [61], [62], [68], [69], [70], [71], [72], [74], [75], [76], [78], [80], [82], [84], [87], [88], [89], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [104], [112], [116], [118], [119], [120], [121], [122], [125], [127], [128], [129], [130], [132], [133], [138], [139], [140], [141], [106], [114], [108], [134], [109], [110], [111], [136], [142], [143], [137]
Jitter	[61], [68], [69], [74], [76], [80], [82], [99], [102], [113], [115], [118], [132], [133], [138], [106], [114], [108], [134], [136]
Resource efficiency	[23], [68], [71], [73], [74], [76], [77], [78], [85], [86], [92], [93], [97], [98], [99], [100], [114], [109], [110]
Supported number of additional resources	[61], [74], [77], [87], [115], [121]

The second most commonly addressed attributes are jitter, and resource efficiency, which are subject to optimization by 24% and 23% of the primary studies respectively. TSN can contribute to resource efficiency in 5G networks by its ability to support fine-grained, deterministic scheduling of network resources. This allows TSN to allocate network resources in a precise and predictable manner, optimizing the use of network resources and reducing congestion. Furthermore, 7% of the primary studies focus on the optimization of additional resources like the supported number of time-sensitive and/or background applications. Overall, 5G networks are designed to support a wide range of applications and services with different set of requirements, including high data rates, low latency, and high reliability.

Many primary studies also address optimization of various types of costs in the context of TSN-5G integration as shown in Fig. 14. Optimization of bandwidth cost in TSN-5G integration is the most studied topic, which is addressed by 14 primary studies. Furthermore, optimization of the costs of "Complexity and implementation", "infrastructure", and "cost of additional network resources" in TSN-5G integrated systems are addressed by 6 primary studies each. Similarly, a few studies have also addressed optimization of product costs, power consumption, and other resources (e.g., flow acceptance ratio) in TSN-5G integrated systems as shown in Fig. 14. Implementing TSN-5G networks can be expensive, as it requires the deployment of additional hardware and software. Note that some primary studies address optimization of more than one type of costs (Table 10).

Table 10
A summary of primary studies according to various types of cost optimization in TSN-5G systems.

Type of cost	Reference to the paper
Power consumption	[24], [68], [69], [139]
Bandwidth	[23], [69], [70], [73], [82], [86], [98], [118], [121], [138], [114], [109], [142], [143]
Product cost	[98], [139]
Complexity and implementation	[61], [62], [73], [78], [82], [112]
Infrastructure	[69], [72], [82], [105], [115], [108]
Cost of additional network resources	[73], [84], [85], [86], [92], [110]
Others	[81], [123]

Table 11
A summary of primary studies according to the type of design of TSN-5G integrated systems.

Type of design	Reference to the paper
Software design	[23], [24], [25], [61], [62], [68], [71], [74], [75], [76], [77], [79], [80], [81], [82], [83], [84], [85], [86], [87], [90], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [103], [112], [115], [116], [117], [118], [120], [122], [123], [124], [125], [126], [127], [128], [130], [138], [139], [141], [132], [133], [114], [107], [108], [109], [110], [135], [136], [142]
Hardware design	[60], [69], [87], [102], [103], [119], [121], [130], [131], [138], [134], [111]

4.5.2. Purpose of contribution – design

We identified that 72% (59 studies) of all the primary studies provide software design for the technique to integrate the TSN and 5G technologies. Furthermore, we observe that only 12 primary studies (15% of the total) present hardware design for the TSN and 5G integration. We also note that only three primary studies [103,130,138] (Table 11) addresses both the software and hardware design of the suggested approach for TSN-5G integration. TSN-5G hardware devices need to have certain capabilities including support for IEEE 802.1 standards, clock synchronization, QoS mechanisms such as packet classification, scheduling, and traffic shaping, etc. Overall, the hardware design of TSN-enabled devices in a 5G network will depend on the specific requirements of the application, however it may take some time before TSN-5G devices become widely available on the market.

4.5.3. Purpose of contribution – evaluation

We observe that a large majority of the primary studies (49 studies) use empirical evaluation for the proposed technical contributions. On the other hand, 20 primary studies use formal analysis to evaluate the proposed technique(s) for TSN-5G integration. Fig. 15 shows the number of primary studies per evaluation setup. The empirical analysis is mostly used in our set of primary studies (Table 12), assuming mostly a simulated network in N3, OMNeT++, or other simulation tools using synthetically generated workloads. These tools include a TSN module, as well as a 5G module to simulate TSN-5G networks. The choice of the simulation tool will depend on the specific requirements and goals of the simulation.

The majority of the primary studies (29 studies) use simulated networks for their empirical evaluation, while 19 studies use a real network to perform the evaluation of their TSN-5G suggested technique/approach as shown in Fig. 15(a). We note that there are no

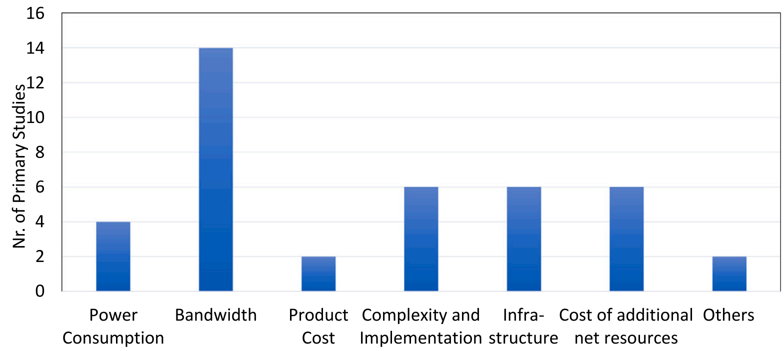
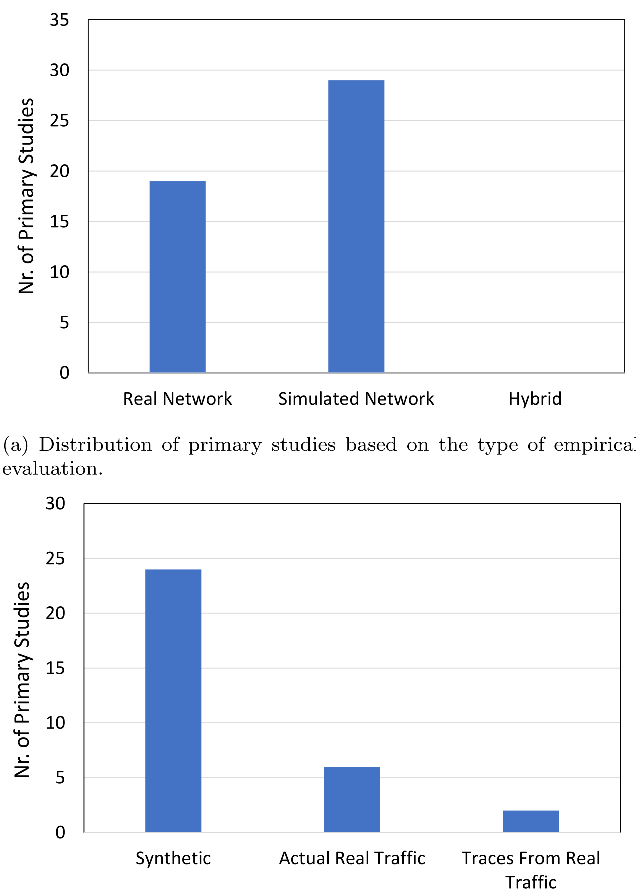


Fig. 14. Number of primary studies addressing various types of cost optimization in TSN-5G integrated systems.



(a) Distribution of primary studies based on the type of empirical evaluation.

(b) Distribution of primary studies based on the type of workload used for the empirical evaluation set up.

Fig. 15. Empirical evaluation strategies used by the primary studies.

publications of type hybrid, considering an integration between real hardware and simulated network components. Another part of the empirical evaluation is the type of workload used in the evaluation set up as shown in Fig. 15(b). We notice that the majority of primary studies (24 studies) use a workload of type synthetic, while there are six primary studies having actual real traffic on their evaluation set up, and two primary study using traces from real traffic. Considering the immature nature of TSN-5G networks, it is hard for the researchers to test and evaluate their approaches using real traffic from an established TSN-5G network.

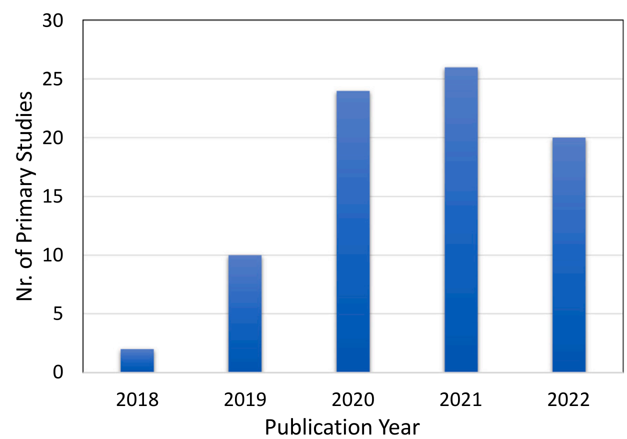


Fig. 16. Publication trend in the research on TSN-5G integration.

4.6. *Analysis based on the domain*

The domain where a technique or framework is applied can be generic, or specific depending on the focused area. As shown in Table 13, 55 primary studies (67% of the total) provide domain-agnostic techniques for the integration of TSN and 5G technologies. There are 22 primary studies (24% of the total) that are focused on the industrial automation domain. There are only three primary studies that focus on the automotive domain. The research on TSN-5G integration is still in its early stages which explains the large number of primary studies that have no concrete application domain in focus.

4.7. *Publication trends*

This subsection presents the publication trends based on the extracted data from the primary studies, thereby addressing the second research question: *RQ2: What are the publication trends of TSN and 5G integration?* To answer this question, we extract the year of publication and venue from each primary study.

Publication year. As shown in Fig. 16, publications in this research area commenced in 2018 after the initial delivery of 3GPP Release 15 in late 2017, which was the first full set of 5G standards. This shows that the research area is still in its infancy. The number of primary studies started to increase in 2019, 2020, and 2021 with 10, 24 and 26 publications respectively. The results also show that the interest of researchers in the area is continuously growing.

Publication venues. We analyze the primary studies based on the publication type, which can be a journal, a conference, a workshop, or a book chapter. The results reveal that most of the primary studies (47 out of 82) are published in conferences. 24 primary studies are

Table 12
A summary of primary studies according to the empirical evaluation strategies.

Empirical evaluation		Reference to the paper
Type of evaluation	Real network	[23], [60], [72], [82], [87], [102], [103], [104] [116], [118], [119], [121], [132], [133], [138], [134], [111], [136], [137]
	Simulated network	[23], [61], [69], [70], [77], [80], [81], [84], [85], [86], [92], [95], [96], [97], [98], [99], [101], [113], [115], [117], [120], [106], [122], [127], [140], [108], [109], [110], [142]
	Hybrid	–
Type of workload	Synthetic	[61], [69], [71], [74], [81], [82], [84], [85], [86], [87], [95] [113], [115], [106], [121], [122], [127], [134], [136], [137], [108], [109], [110], [142]
	Actual real traffic	[23], [102], [103], [104], [138], [111]
	Traces from real traffic	[98], [116]

Table 13
Number of primary studies per each type of domain.

Type of domain	Number of primary studies	Reference to paper
Generic	55	[23,25,68–75,77,79,81,82,85–88,91–97,99,100,103–105,107,110,112,113,115,117,118,121–133,135–137,140,141]
Industrial automation	22	[24,60,61,76,78,80,83,89,90,98,102,106,108,109,111,116,120,130,134,138,139,143]
Automotive	3	[62,101,142]
Smart cities	1	[119]
Medical	1	[84]

Table 14
Publication venues with at least 2 primary studies.

Venue name	Acronym	Type	#papers
IEEE International Workshop on Factory Communication Systems	WFCS	C	6
IEEE International Conference on Emerging Technologies and Factory Automation	ETFA	C	6
IEEE Communications Standards Magazine	–	J	5
IEEE Network	–	J	3
IEEE Access	–	J	3
IEEE International Conference on Edge Computing	EDGE	C	2
International Conference on Information and Communication Technology Convergence	ICTC	C	2
IEEE International Conference on Communications	ICC	C	2

published in journals with at least 3 journal publications per year since 2019, 1 primary study is a book chapter, while the remaining primary studies are part of our grey literature search consisting of white papers, web pages, or forums.

Another classification is based on the targeted publication venues. In Table 14, we list the publication venues where at least two primary studies have been published. The IEEE International Workshop on Factory Communication Systems (WFCS) and the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) have published the highest number of primary studies to date.

5. Results: Horizontal analysis

In this section, we investigate the possible relations that might exist between different categories of the data extracted from the primary studies. The purpose of this analysis is to highlight the main focus and identify the potential gaps in the existing research on the integration of TSN and 5G technologies. This analysis aims to provide an answer to the third research question, *RQ3: What are the limitations of TSN-5G integration?*

We analyze the relationship between two different categories using bubble plots in which the size of the bubble corresponds to the number of primary studies addressing the pair of categories intersecting each other. The first bubble plot, depicted in Fig. 17, shows the relationship between the technical contribution classification (along the vertical axis) and the research type classification (along the horizontal axis). As can be noticed from the plot, the majority of the existing research in the area is focused on presenting solution proposals and validation research for TSN-5G integration techniques. 35 primary studies provide solution proposals for TSN-5G integration architectures. Furthermore, there are 26, 14, and 22 primary studies that provide solution proposals for time synchronization, flow management, and resource management in the context of TSN-5G integration respectively. Similarly, there are 42, 25, 12 and 23 primary studies that present validation research for integration architectures, time synchronization, flow management, and resource management respectively. In addition, there are a few primary studies that present a conceptual proposal for TSN-5G integration. It can be observed in Fig. 17 that there are no evaluation research and experience papers that provide a technical contribution (integration architectures, time synchronization, flow management, and resource management) for TSN-5G integration. This identifies a potential gap in the existing research and provides opportunities for further research on the integration of TSN and 5G technologies.

The relationship between the technical contribution classification and the contribution type classification in the primary studies is illustrated by the bubble chart in Fig. 18. It can be observed from the bubble chart that the majority of primary studies provide a method/technique/approach or a model/framework/architecture for the integration of TSN and 5G technologies. For instance, there are 37, 26, 7, and 17 primary studies on TSN-5G integration that provide a method, a technique, or an approach for the integration architectures, time synchronization, flow management, and resource management respectively. Similarly, there are 27, 17, 16, and 19 primary studies on the integration of TSN and 5G technologies that provide a model, an architecture

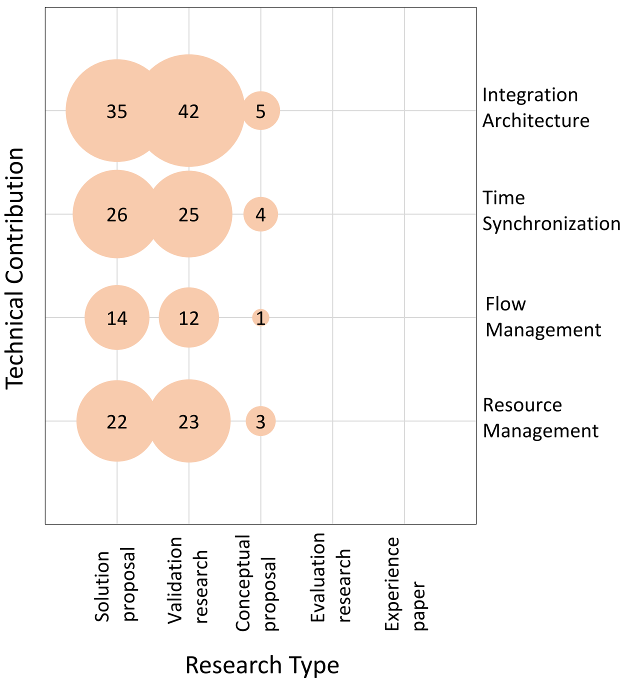


Fig. 17. Relationship between the research type and technical contribution classifications in the primary studies.

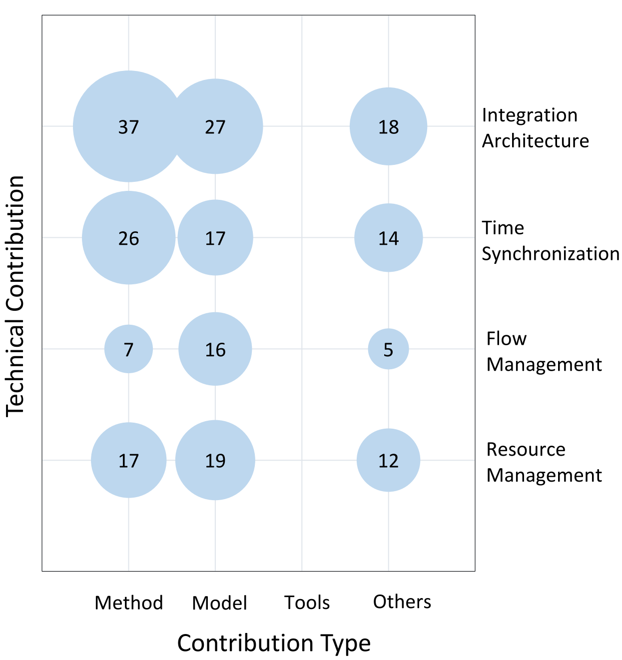


Fig. 18. Relationship between the technical contribution and contribution type classifications in the primary studies.

or a framework to support the integration architectures, time synchronization, flow management, and resource management, respectively. Integration architecture is addressed in most of the primary and this can be motivated by the converged nature of a new network which still needs a lot of research and investigation.

The bubble chart in Fig. 18 also indicates that there are a few primary studies that provide other types of contribution with regards to the TSN-5G integration architecture, time synchronization, flow management, and resource management, e.g., solutions for TSN on 5G fronthaul [75]. One major gap that we identify in the existing research on the TSN-5G integration is that there is no tool support available with any of the proposed techniques. This is evident from zero entries in the "Tools" column in Fig. 18. Note that tools serve as a vehicle to transfer research results from academia to industry. This calls for the research community to develop prototypes of a tool that implements the scientific techniques for the integration of TSN and 5G technologies.

6. Fleiss kappa analysis

Fleiss kappa is a statistical analysis that can help in defining the level of agreement among the researchers during the selection phase of this systematic literature review. We will use it to address the possible threats to validity and to ensure the reliability of our study inclusion decisions.

The idea of such statistical analysis came firstly from Cohen [144] who considered a case when two raters were trying to rate or categorize a set of subjects. He introduced a kappa value to measure the level of agreement between two raters. Fleiss kappa statistical analysis [145] was introduced to eliminate the limitation of only two raters. We use this method in the early phase of the selection of publications to access the reliability of agreement among the researchers performing this study.

To perform the Fleiss Kappa analysis, three researchers were assigned 25 publications each. The publications were selected randomly from the search pool of publications taken after the removal of duplicates and impurities as shown in Fig. 2. The researchers independently categorize those publications as Relevant, Not Relevant, or Not Clear based on title, abstract, keywords, and full-text skimming (if needed). From the Fleiss Kappa point of view, the 25 papers are the subjects that need to be categorized by the 3 raters into 3 categories. **After applying the analysis, we calculated the overall agreement among the researchers on a value of 83% which indicates a strong level of agreement among the raters** [146]. Based on this statistical analysis we conclude that the researchers had a strong level of agreement when selecting the relevant papers for the systematic literature review.

7. Threats to validity

To prove the quality of our study, we discuss in detail the possible threats to validity and how we managed to mitigate them. There are three types of threats we address: external, internal, and construct validity.

7.1. External validity

The external threat to validity deals with the generalizability of the results [147]. A possible threat can be a set of selected studies that cannot fully represent the state of the art on TSN-5G integration. To mitigate this potential threat, we make sure to choose multiple data sources which are four of the largest and most complete databases in computer science, computer engineering, software engineering, and systems engineering: ACM Digital Library, IEEEXplore Digital Library, Scopus and Web of Science. After the automatic search, we implement the recursive backward and forward snowballing strategy to be sure about the coverage of our study.

Considering the pilot studies in our systematic literature review, we apply well-defined and constructed inclusion and exclusion criteria. Excluding the studies which are not written in English can be a possible threat, but considering the fact that English is the de-facto language for all the scientific papers, this threat can be omitted.

7.2. Internal validity

Internal validity refers to the inaccurate settings or variables that may cause a negative impact on the design of our systematic literature review. We mitigated this threat by following well-established guidelines when defining the data extraction form and the process which we follow in this study. Furthermore, we cross-analyzed all the parameters in the data extraction form to identify and solve any potential issues with the consistency of the extracted data.

7.3. Construct validity

Construct validity refers to the representativeness of the selected studies [22]. The recursive backward and forward snowballing makes us confident on the coverage of our study that we did not miss any relevant study.

In the beginning, we collected the research studies using the search string. The definition of the string can be a potential threat to validity. All the researchers involved in this study discussed together every parameter of the search string by following a rigorous process. This minimizes the threat to construct validity. After the automatic search, studies were analyzed by well-documented inclusion and exclusion criteria. To prove the reliability of the review, three of the researchers independently classified a set of common studies and applied the Fleiss kappa statistical analyses [145] as described in Section 5, achieving a kappa value of 83% which means a strong agreement among the researchers.

7.4. Conclusion validity

The conclusion validity refers to the relationship between extracted data and obtained findings [147]. We mitigated this potential threat by systematically documenting by using a well-defined process and by providing a replication package that allows replicating each step of the process. The replication package is freely accessible.[4] The definition of the data extraction form can be a potential threat to conclusion validity. To mitigate this threat we (i) let the parameters emerge from the pilot studies and refine the parameters throughout the entire data extraction activity, and (ii) make all the researchers actively involved in the definition of the extraction form as well as in the extraction and analysis of the data.

8. Related work

There are a few systematic reviews and surveys conducted in the area of TSN and 5G with a special focus in 3GPP Releases. For example, the study in [148] presents an overview of 3GPP Releases focusing on the extensive enhancements to achieve backward compatibility in the subsequent releases. Similar studies are performed by Jerichow et al. [149], Nwakanma et al. [150], and Atiq et al. [32].

Jerichow et al. [149] present an overview of public networks that are integrated with non-public networks within the scope of the 3GPP Release 16 architecture. Furthermore, they also discuss security concepts of 5G non-public networks. Nwakanma et al. [150] review the implementation possibilities and challenges of 3GPP Release 16 in Industrial Internet of Things and mission-critical communications. Atiq et al. [32] comprehensively analyze the recent standardization efforts and developments in IEEE 802.11 and 5G, and present a set of use cases enabled by wireless TSN. The authors provide insights in wireless TSN considering time synchronization between 802.11 or 5G and TSN devices, techniques to achieve reliability requirements, and mapping QoS profiles with the TSN defined traffic.

Jun et al. [151] perform a detailed survey of 3GPP standardization activities to ensure low latency at the network level. Furthermore, they investigate the time-sensitive communication in Release 16 and 17, including the time synchronization in a TSN-5G architecture that conforms to the two Releases. Wollschlaeger et al. [152] also present an overview of the 5G evolution among 3GPP Releases starting with Release 15 and concluding with features expected from Release 17. The ongoing standardization in 3GPP regarding the integration of TSN and 5G systems is also addressed by Striffler et al. [78]. The authors identify open issues that still need to be addressed in terms of time synchronization, session continuity, and scheduling of different traffic streams.

On the other hand, there are several works focused on reviewing TSN and its potential use cases [11,153–155]. Lo Bello et al. [11] surveys TSN in industrial communication and automation systems while discussing core TSN standards and novel features which make TSN an enabler for several cutting-edge technologies. While Lo Bello et al. [11] remain generic, Samii et al. [154] focus on the automotive domain. They review the TSN standards in light of possible use cases in automotive systems. In addition, Deng et al. [155] also takes the automotive use case as an example to discuss the application of TSN in automobiles. The aim of the article is to provide an overview of recent advances and future trends in real-time Ethernet modeling and design methodologies for AVB and TSN. It surveys the current state of the field and provides references for researchers who are interested in this area. Moreover, Craciunas et al. [153] overviews the scheduling problem arising from time-sensitive network technologies like TTEthernet and TSN. The authors describe the main differences between two technologies, and they also describe the scheduling constraints that enable real-time temporal behavior on the level of individual communication streams. Reviewing the existing surveys on TSN, we observe that none of them is focusing on the converged TSN-5G system.

A comprehensive survey of the IEEE TSN and IETF DetNet standards targeting the support for ultra-low latency (ULL) is presented by Nasrallah et al. [7]. This work provides an in-deep survey of the development of IEEE TSN standards and highlights significant milestones illustrating the shift from Audio Video Bridging (AVB) to TSN. Flow synchronization, flow management, flow control, and flow integrity are some of the addressed aspects of TSN including:

- Generic Precision Time Protocol to accomplish time synchronization of data.
- YANG data models to provide a framework for periodic status reporting and the configuration of bridges.
- Resource Allocation Protocol (RAP) to achieve a distributed TSN Control Model since SRP is restricted to A/V applications having a limited number of SR classes. RAP improves scalability by leveraging the Link-Local Reservation Protocol (LRP) to support all TSN features.
- Gate Control List used for the TSN flow control and IEEE 802.1Qbv Time-Aware Shaper (TAS) which is applicable for ULL requirements when all time-triggered windows are synchronized.

On the other hand, this study also addresses the key components in 5G standards for supporting ULL mechanisms. Some of the surveyed components are the Common Public Radio Interface (CPRI) which provides the specifications for packing and transporting baseband time domain and eCPRI to reduce the effective data rate. In addition, this survey also presents an overview of the main ULL research directions in the 5G wireless access segment and on TSN network. This survey covers the link and network layer latency reduction standards covering studies up to July 2018, while B. Briscoe et al. [156] surveys general techniques for reducing latencies in Internet Protocol (IP) packet networks covering studies up to August 2014.

Furthermore, there is also a systematic review of URLLC (Ultra-Reliable Latency Communication) technology of 3GPP presented in

[4] https://github.com/zenepe1/TSN-5GReplicationPackage.

[157]. URLLC is a feature that will be covered by 5G and beyond 5G. This review analyzes the URLLC networking trend in wireless and wired communication. It mentions four technologies: Near area time deterministic wired network (IEEE TSN, 802.1Qx), Mobile time deterministic network (5G TSC, TSN-TT), broad area deterministic wired network (IETF DetNet) and metro deterministic wired network (OIF FlexE, ITU-T SG15 G.mtn). This study also surveys all the patents related to low-latency technology, patents related to high-reliability technology, and patents related to mobile network technology, showing the extreme increase in the number of patents based on 3GPP specifications.

Time Synchronization is an important part of latency in low-latency applications. All gPTP systems exchange timing information between different network devices on the control plane. The load created in the control plane due to the time synchronization can have a great impact on low-latency applications. A solution to mitigate the load created in the control plane is to use a centralized time synchronization system where timing information messages are exchanged only between a central controller and individual network devices. This approach is similar to software-defined networking (SDN) [158,159] even though SDN technology in wired and fixed network is more advanced than the SDN-based mobile network developments [160].

Another review of URLLC as a key enabler of mission-critical services is presented in [20]. It overviews the state of the art of URLLC in the physical layer, link layer, and network layer summarizing the potential implementation methods of URLLC. In addition, this study also illustrates the challenges of mobile systems to support the integration of URLLC technology and identifies the need for meaningful models to fit practical scenarios. All these studies have surveyed the 3GPP Releases including the key components of 5G standards [161] and TSN standards [11,162] separating them from each other.

5G-ACIA [18] aims at supporting 5G in the industrial domain and provides an insight overview of 5G in industrial applications, including the possible integration concepts and migration paths. There are a few white papers published by this organization that outline the critical requirements for interoperability and features of 5G. The integration of TSN and 5G is also addressed by this forum. The forum also explores how and why should the integration of TSN and 5G be applied in the industry. Their baseline is the 3GPP Release 16 for 5G specifications and IEEE standards for TSN specifications. We consider this paper since it provides not only an overview of the standards but also shows the TSN and 5G integration for various industrial automation use cases, i.e., controller-to-controller, controller-to-device, and device-to-compute communication.

Moreover, Parvez et al. [163] present several latency-critical applications which need to be supported by 5G. They also demonstrate the typical latency and data rate requirements for different mission-critical services, e.g., factory automation, robotics, virtual reality, and healthcare. Various solutions on RAN, Core Network, or caching solutions, are used to achieve low latency on a 5G system. 5G is also a promising solution for autonomous driving meeting the connectivity requirements of V2X communication for higher levels of autonomy [164].

The usage scenarios of 5G are also presented by Navarro-Ortiz et al. [165]. They present the most significant use cases expected for 5G including their scenarios and traffic models. Although this survey is focusing only on 5G, it performs useful analyses not only on the characteristics and requirements for 5G communications but also on 5G usage scenarios allowing 5G stakeholders and researchers to evaluate the performance of 5G solutions under the most critical requirements. Furthermore, 5G should be adapted to a wide range of scenarios such as indoor, urban, suburban, rural areas, etc, which will set new requirements for 5G channel modeling [166]. In addition, Ai et al. [161] have identified significant 5G-based key technologies for high-speed railways to develop innovative communication network architectures that ensure high-quality transmissions for both passengers and railway operations and control systems.

Recse et al. [167] and Kaloxylos [168] advocate network slicing to be the key enabler to realize 5G in IoT. The use of the network slicing method can effectively guarantee the QoS requirements of different services by splitting the existing physical network to form multiple independent logical networks with customized services [169]. Even though the integration of TSN and 5G is not considered by the authors, the investigated technologies can provide a good foundation for converged wired and wireless architecture considering 5G. However, the research on the application of network slicing over TSN networks [82] is still in its infancy and the telecommunication organizations are still working on the standardization of such technology.

Scanzio, Wisniewski, and Gaj [170] perform an analysis of the state of the art in the area of heterogeneous industrial networks. This survey investigates both wired and wireless technologies considering technological aspects and performance targets, e.g., dependability. It also highlights the main challenges and communication requirements of industrial applications. 5G is also one of its targeted wireless technologies but the integration of wired and wireless technologies is still a challenge that they aim to consider as their future work.

Although 3GPP standards offer the possibility to converge TSN and 5G networks, a comprehensive overview of TSN-5G integration scenarios and a structured research map of the area is still missing. In this context, with this systematic literature review, we attempt to present all the current studies conducted in the scope of TSN-5G integration, while identifying the gaps in the existing research and highlighting further research opportunities for researchers and practitioners.

9. Conclusions

In this article, we presented the planning, execution, and results of a Systematic Literature Review (SLR) on the integration of TSN and 5G technologies. The SLR provides a holistic overview and structured map of the state of the art research on TSN-5G integration. We identified 189 research studies in the initial phase of search and selection. After several refinements, we selected 82 of them as the primary studies that focus on the integration of TSN and 5G technologies. We extracted the required data from these primary studies by using a well-defined and thorough data extraction process. The extracted data was then analyzed and synthesized to answer the three research questions posed in this SLR.

The first research question was answered by analyzing the primary studies according to their technical contributions. We noticed that 74% of the studies follow the architecture proposed by the 3GPP working group, while still encountering difficulties on time synchronization, resource management, and flow management of the integrated system. Furthermore, the most commonly used time synchronization approach is the transparent clock approach that is proposed in the 3GPP specification. In addition, 72% (59 studies) of all the primary studies provide software design, while only 12 primary studies (15% of the total) present hardware design for the TSN and 5G integration. The majority of the primary studies (29 studies) use simulated networks for their empirical evaluation, while 19 studies use a real network to perform the evaluation of their TSN-5G suggested technique/approach.

The second research question was answered by classifying the primary studies according to well-defined classification criteria and showing the research trends in the area of TSN-5G integration. The results show that the interest of researchers in the area is continuously growing. The IEEE International Workshop on Factory Communication Systems (WFCS) and the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) have published the highest number of primary studies to date.

To answer the third research question, we used horizontal analysis to investigate the relationship between various sets of categories in the proposed classification. This analysis resulted in the identification of potential gaps in the research area and opportunities for future research. Among the others, it calls for the research community to develop prototypes of a tool that implements the scientific techniques for the integration of TSN and 5G technologies.

The results of this study are comprehensive enough for researchers and practitioners in identifying current research trends, potential gaps, and future research directions in the context of integrating TSN and 5G technologies. In the future, we plan to provide an approach for timing synchronization between TSN and 5G following the integration architecture suggested by the 3GPP working group. Another contribution to the research community would be to evaluate the timing approach using one of the well-known simulation frameworks, named OMNet++.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zenepe Satka reports financial support was provided by Sweden's Innovation Agency.
Zenepe Satka reports a relationship with Sweden's Innovation Agency that includes: funding grants.

Data availability

No data was used for the research described in the article.

Acknowledgments

The work in this paper is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) via the PROVIDENT, DESTINE, and INTERCONNECT projects, and the Swedish Knowledge Foundation via the DPAC and HERO projects. We would like to thank all our industrial partners, especially Arcticus Systems, HIAB, and Volvo Construction Equipment.

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