Abstract—New degrees of flexibility regarding the communication infrastructure are necessary to realize the vision of Industry 4.0, i.e., the further advancement of digitalization in factories. The 5G standard will push into this new area of industrial communication with Release 16. In this paper, we explore ongoing standardization activities related to the integration of 5G and time-sensitive networking as a fundamental building block for flexible production. We provide a condensed summary of recent developments in 3GPP standardization and identify open issues that still need to be addressed in the future. We discuss the aspect of time synchronization in detail and make a recommendation for a way forward from the perspective of vertical applications.

Index Terms—5G, TSN, wireless, 3GPP, IEEE 802.1, industry 4.0

I. INTRODUCTION

The 5th generation cellular standard (5G) will not only bring enhanced mobile broadband (eMBB) communication and massive machine-type communication (mMTC), but also ultra reliable low latency communication (URLLC). More specifically, URLLC and mMTC will further advance wireless connectivity into technology fields like automated driving (cellular vehicle-to-everything) and will support the deployment of massive sensor networks for Internet of Things (IoT) applications [1]. Another important new area for 5G will be industrial communication. Introducing new reliable and low-latency wireless connectivity to applications that have been traditionally served through wired communications links will provide further flexibility to manufacturing.

New degrees of flexibility regarding the communication infrastructure are necessary to realize the vision of Industry 4.0 (I4.0), i.e., the further advancement of digitalization in factories. Devices become increasingly mobile (e.g., automated guided vehicles) and production lines become increasingly modular and reconfigurable. In order to be viable alternative to wired communication, 5G-based wireless communication has to preserve reliability despite the non-deterministic behaviour of wireless links [2]. An extensive overview of current research on URLLC related to 5G and Time-Sensitive Networks (TSN) can be found in [3], [4].

A typical real-time communication requirement for highly automated production systems in today’s factories is an end-to-end latency of 1 ms [1]. Wired communication technologies that meet this requirement include EtherCAT [5], PROFINET IRT [5] and Sercos III [5]. However, interworking between these technologies requires significant effort. Consequently, the IEEE started a standardization activity for so-called TSN in 2012, a vendor agnostic technology for reliable low-latency communication. It is described in the corresponding IEEE 802.1 standard, an overview of which is given in Table I. A key principle of TSN is to assign priorities to different traffic streams. A traffic scheduler (IEEE 802.1Qbv, now included in IEEE 802.1Q [6]) is then employed to guarantee the successful transmission of high priority traffic by reserving specific time slots for each high priority stream. Fundamental prerequisites for TSN are time synchronization of all network infrastructure elements (IEEE 802.1AS [7]) in the order of microseconds and the configuration of all participants according to the scheduler. For the latter, the network control can be either fully centralized, fully decentralized, or a hybrid of both. A centralized architecture allows for more efficient scheduling but is not as scalable as a decentralized architecture.

In this paper, ongoing standardization activities related to the integration of 5G and TSN are explored. An overview of current developments at the 3GPP is given and open topics that still need to be addressed in the future are identified. Section II summarizes the requirements for I4.0 use cases collected in the 3GPP. Section III provides an overview of architecture related efforts for I4.0, including 5G and TSN integration. Open topics are discussed in Section IV. The paper ends with a short conclusion in Section V.

II. INDUSTRIAL USE CASES AND REQUIREMENTS

As of today, there are two main technical reports (TRs) that study the use cases and requirements for the integration of TSN in 3GPP Release 16.

TR 22.804 [8] contains an extensive collection of use cases and requirements for communication for automation in vertical domains in general. Most relevant for wireless TSN are the use cases related to "Factories of the Future" (section 5.3), which are focused on automation in industry and smart grid applications. TR 22.804 is not specifically related to TSN, but it nevertheless already presents requirements regarding the necessary precision of clock synchronization.

In TR 22.821 [9], use cases and requirements for the integration of Industrial Ethernet [5] and 5G systems are collected.
The main assumption is that wireless communication will replace traditionally wired links for specific applications in industry scenarios, e.g., when machine parts are moving or in aggressive chemical environments. A large portion of the existing network would still remain wired. With respect to TSN specifically, three features are considered relevant for high performance applications in industrial automation, namely clock synchronization (IEEE 802.1AS), time-aware scheduling (IEEE 802.1Qbv, merged into IEEE 802.1Q), and frame preemption (IEEE 802.1Qbu, merged into IEEE 802.1Q).

The requirements presented in the reports TR 22.804 [8] and TR 22.821 [9] have been consolidated in the 3GPP specification document TS 22.104 [10], with focus on cyber-physical control applications, and TS 22.261 [11] with focus on general requirements. This class of vertical applications requires particularly high communication service availability (≥ 99.999%) and often also very low end-to-end latencies (< 1 ms). An overview of relevant requirements for this application class is given in Table II.

A new study item, FS_eCAV [12], approved in March 2019, intends to expand upon these documents. The goal is to identify further use cases for cyber-physical control applications in vertical domains and based on these, enhance the collected requirements to give a more precise idea of what is needed for 5G to be successful in vertical applications.

Aside from 3GPP, also IEEE and International Electrotechnical Commission (IEC) collected use cases in the document IEC/IEEE 60802 [13]. In contrast to TR 22.804 [8], which covers a multitude of vertical domains, the IEC/IEEE report is focused specifically on TSN in industrial automation.

### A. Availability

According to 3GPP TS 22.104 [10], industrial communication applications require a communication service availability of 99.999% to 99.999999%. TR 23.725 [14] suggests in “Key Issue #1: Supporting high reliability by redundant transmission in user plane”, that this reliability might not be achievable with single path links. Instead, multipath transmissions can be used to add redundancy and thus increase communication service availability at the cost of increased resource usage. TR 23.725 [14] proposes five different approaches to enabling redundant transmission paths in the 5G system. These approaches differ mainly in what part of the transmission chain is duplicated.

- **Duplicate protocol data unit (PDU) Sessions**: Two approaches propose the duplication of PDU sessions. They differ in the starting point of the duplicated path. One approach assumes one user equipment (UE) at the device, duplicating the path from the UE. In addition, the other approach assumes the duplication of UE at the device.

- **Duplicate N3 tunnels**: Two approaches propose the duplication of N3 tunnels between radio access network (RAN) and user plane function (UPF). One approach proposes the duplication of the RAN as well as the data transmission over N3, while the other approach only considers the duplication of the data transmission.

- **Replicator function**: The last approach proposes the introduction of a "replicator" that makes the 5G system aware of duplicated data streams and allows for optimized treatment.
B. Latency

3GPP TS 22.104 [10] requires a maximum end-to-end latency of 0.5ms for some motion control application aspects. TR 38.825 [15] evaluates whether one-way latency targets can be met using Rel-15 architecture. The maximum latency requirement can be achieved with Rel-15 architecture as long as the sub-carrier spacing (SCS) is 30 kHz or higher.

C. Synchronization accuracy

In regard to synchronization accuracy between gNB and UE (over Uu), the requirements in TS 22.104 [10] call for $<1\mu s$ for deployments of various sizes. According to the evaluation results in TR 38.825 [15], these requirements can be achieved without propagation delay compensation as long as the distance between sites does not exceed approximately 200 m. For larger deployments, propagation delay compensation will be necessary. Additionally, higher SCS achieve better synchronization accuracy. For the synchronization accuracy between gNB and TSN GM clock, three options were considered in TR 38.825 [15]. (1) A local on-site GNSS receiver as TSN GM clock, (2) a local on-site TSN GM clock, and (3) a remote TSN GM clock using a cascaded precision time protocol (PTP) capable transport network connection. For options 1 and 2, the required synchronization accuracy can be achieved without issue. For option 3, the timing error depends on the number of PTP hops between the TSN GM clock and the gNB, where for larger number of hops the timing error accumulates.

D. Session continuity

An important issue of an integrated 5G-TSN network is how to meet reliability, latency, and synchronization requirements despite device mobility. In TR 23.725 [14] the key issues #2 and #3 describe the need to keep meeting requirements during handover and enhance session continuity. The proposed solutions enhance the procedures already described in TS 23.502 [16].

- **N9 tunnel:** An N9 forwarding tunnel between source- and target-Uplink Classifier (ULCL) is introduced. Any uplink or downlink traffic is forwarded through this tunnel until the active traffic flow ends or a pre-configured time delay has passed.
- **PDU session anchor (PSA) relocation:** Session continuity is enhanced by switching from source to target PSA during a handover, if that alternative path, for example, allows for greater reliability or provides better quality of service (QoS).
- **Handover coordination:** The presence of multiple redundant transmission paths is assumed. The handover performance can then be improved by coordinating the handover timings such that the handover of redundant UEs do not happen simultaneously, preserving their function.

III. Architecture

In broad terms, TSN is an ethernet-based layer 2 technology for deterministic, low latency, and high reliability communication. It is mainly build on four pillars. (1) Highly accurate time synchronization, (2) bounded low latency, (3) high reliability, and (4) resource management.

An example of a fully centralized TSN network is shown in Figure 1. The TSN endpoints are the devices in the network that either generate or consume the information that is transmitted, e.g. sensors and actuators. These endpoints are connected by TSN bridges that act as forwarding relays. The bounded low latency and high reliability of the time-sensitive communication is achieved by scheduling the different traffic streams and preventing interference by low priority traffic with frame preemption. To achieve this from endpoint to endpoint, the TSN bridges are synchronized to the TSN master clock via PTP messaging. With all the bridges synchronized to the same time, the central network controller (CNC), having a complete view of the network, can configure each bridge to achieve the end-to-end requirements communicated by the centralized user configuration (CUC). The CUC in turn derives these requirements from the applications.

The 5G network, on the other hand, is a wireless communication network. The 5G architecture in detail is described in TS 23.501 [17], a rough overview is given in Figure 2. The network can be divided into RAN and core network (CN). A UE is connected to the gNodeB (gNB) via the air interface. The gNB is then logically connected to the different network functions like the UPF. The different functions in a 5G network are not fixed to specific physical entities. Due to virtualization the functions can be performed according to the requirements of the network, e.g. on-site in the gNB or in the edge cloud.

In contrast to a wired TSN network, links are not preplanned, but can be created, removed, and changed dynamically. The report TR 23.734 [18] gives details on functionalities in a 5G system that are required to support the use cases for vertical industries as described in TR 22.804 [8]. It is based on the 5G service requirements for vertical domains described in TS 22.104 [10], and the more general 5G service requirements.

A. Integration Architecture

Three approaches have been proposed on how to enhance the 5G architecture to integrate the 5G system with a TSN network.

- **TSN link**: The 5G wireless link exposes the properties of an Ethernet cable to TSN bridges and end stations. However, there is a fundamental mismatch of link behaviours between wireless and wired communication that needs to be addressed. Hence, either the TSN QoS requirements can be preconfigured in the 5G system, which removes the ability to adapt to different scenarios and requirements, or the IEEE TSN standards can be extended to support a "5G system link".

- **TSN bridge / adapted TSN framework**: The 5G system needs an adaptation module that is able to process TSN protocols and information objects, while 5G specific parameters and procedures are not exposed to the TSN. From TSN perspective, no modifications are necessary and the 5G system is a black box. The 5G system handles TSN requests via its QoS framework.

- **Integrated TSN framework**: The 5G system acts as a TSN-compatible entity and exposes its interfaces to the TSN system. This approach would require extensive specification work on the 5G side, as well as the introduction of respective adaptation layers on the TSN side, which might be impractical.

In Rel-16, only the TSN bridge approach will be included.

B. Time Synchronization

Regarding time synchronization, mainly two approaches are under consideration in TR 23.734 [18].

- **Boundary Clock**: In the boundary clock solution, shown in Fig 3, the 5G RAN has a direct connection to the TSN master clock based on IEEE 802.1AS. The RAN, or specifically the gNB, then provides the timing information via 5G broadcast channels to the UEs. With this timing information, the UEs synchronizes the TSN device.

- **Transparent Clock**: In the transparent clock solution, shown in Fig 4, the synchronization is achieved via PTP messages. Any forwarding device has to add the "residence time" to the message, the time delay between ingress and egress port. This can be achieved by either extending QoS classes with a fixed residence time between pairs of ports, or signalling ingress and egress timestamps for residence time measuring.

An approach to introduce such a deterministic delay QoS class is given in solution #17 in TR 23.734 [18]. Using the parameters "Target Delay", "Loss Tolerance", and "Priority", packets can be scheduled to arrive within a predetermined delay. If the target delay is not met, the packet is either dropped or rescheduled, depending on the given loss tolerance (based on the survival time) and priority.

Solution #18 in TR 23.734 [18] details how the QoS classes and requirements can be coordinated between the 5G and TSN networks. For centralized or hybrid TSN networks, the 5G system would connect to the TSN CNC via the TSN AF in a control-plane based approach. In a centralized network, the CNC has knowledge of the network and can therefore communicate QoS requirements. For decentralized TSN networks, the 5G system would connect directly to the TSN bridges in a user-plane based approach, as there is no CNC.

IV. OPEN TOPICS AND WAY FORWARD

Regarding the next steps in standardization, we have already mentioned FS_eCAV [12] and its goal of updating the current use cases and requirements. In the following paragraphs, we adress additional aspects of the topics considered in Sections II and III.
A. Time synchronization

The TSN scheduler assigns different streams to different time slots across the whole network. This is only possible with reliable and precise time synchronization of all nodes in the communication infrastructure. Time synchronization over wireless links faces similar challenges as scheduling, i.e., (1) communication links with variable latencies and (2) varying network topology due to mobility. Additionally, some industrial applications rely on multiple time domains (TS 22.104 [10], Annex D), i.e., a universal time domain and a working clock domain, as shown in Figure 5. The universal time domain provides the overall synchronization for the system with precision in the order of $1 \mu s \ldots 100 \mu s$. The working clock domain provides very precise synchronization in the order of $1 \mu s$ in a small area. For instance, a factory would have one universal clock domain for overall operation synchronization, and multiple working clock domains to synchronize the individual production lines and machines. An important aspect is also the interaction across multiple time domains. When two devices synchronized to different working clock domains need to interact with each other, they can either merge, i.e., synchronize to the same working clock, or stay separate. Based on the time synchronization options given in TR 23.734, the document 3GPP S2-1812419 [19] describes how the merging of multiple working clock domains could be implemented. Further enhancements to 5G system support of multiple time domains specifically, as well as time sensitive communication in general, will be investigated in the proposed study S2-1903647 (FS_IoT) [20].

Boundary clock vs Transparent clock: In Section III B we described the two main approaches to achieve time synchronization between the 5G and TSN networks. In comparing and evaluating these two, the main question is whether they can fulfill the needs and requirements posed in an industrial automation scenario. It is also relevant how extensive the 5G system changes would have to be, to be able to support the solution, and how costly and complex its implementation would be. Both S2-1903371 [21] and S2-1903650 [22] compare the boundary clock and transparent clock approaches, without drawing any conclusions or giving recommendations.

In regards to the RAN, the transparent clock only transmits the 5G system clock but requires the timestamping of messages to synchronize to the TSN clock. Thus, the gNB does not need to track the TSN clock. Only the residence time and the link delay are necessary for a precise time synchronization. The boundary clock has to track and transmit the TSN clock in addition to the 5G clock, but does not need the precise residence time. Thus, as long as the UE can accurately measure the time delay between ingress and egress port, achieving precise time synchronization across multiple devices should be easier with the transparent clock solution.

An important issue we mentioned before is the support of multiple different time domains in one network. TS 22.104 [10] requires the support of up to 32 domains. In the transparent clock solution the gNB still only has to track one clock. However, according to S2-1903650 [22] the capacity on timestamping and duplication towards UEs at UPF limits the number of supportable time domains. The boundary clock solution has every gNB track the different time domains. An extension of the boundary clock solution (#11-4) would avoid this issue by synchronizing all time domains to the 5G system clock. This limits the number of working clock domains, as it basically merges them together. Thus, this solution is not feasible for use cases where multiple different working clock domains are required. In addition, S2-1903371 [21] raises the concern that this approach might not be practicable due to it requiring changes to industrial controllers.

Another important difference between both solutions is the directionality of synchronization. While the transparent clock solution supports synchronization both in uplink (UL) and downlink (DL), the boundary clock solution only allows DL synchronization. In the boundary clock extension #11-4, UL synchronization becomes possible, though at the before-mentioned cost of merging time domains to synchronize to the 5G system clock. Thus, applicable use cases are limited in that regard.

Based on this comparison and evaluation of the time synchronization approaches, the transparent clock solution is more suitable for industrial automation use cases with multiple time domains. Coming to a similar conclusion, at the April 3GPP SA2 meeting, the 3GPP agreed on the transparent clock approach for Rel-16.

B. Session continuity

Session continuity is a core issue for combining mobility and URLLC. With SP-190185 (FS_enh_EC) [23], a new work item on the enhancement of edge computing support in the 5G core was proposed in March. Some of the issues under consideration, e.g. improvements to PSA change and QoS information distribution, are very relevant to the the suggested
solutions for session continuity mentioned in Section II.

C. Scheduling

Scheduling in TSN is based on a timed gate control list. In different time slots, different traffic streams are transmitted. These schedules have to be configured according to the network layout and the requirements of the communicating devices and are distributed to all the bridges in the network. Depending on the size of the network and the number of communication streams, finding an optimal schedule can become a very complex task and integrating 5G will make it even more complicated.

Wireless connections behave differently from wired links. In particular, (1) sudden loss of connectivity to a wireless device can occur due to external factors, (2) device mobility can lead to frequent changes of the network layout, (3) latencies for wireless devices are not necessarily symmetric in uplink and downlink and exhibit more variance. An integrated 5G/TSN scheduler would need to be able to react to the more dynamic communication infrastructure. If the 5G system can be considered a black box, integration from TSN perspective becomes simpler, because configuration options are limited to the outward facing parameters of the 5G system. However this approach is subject to the trade-off of being limited to the QoS classes defined in 5G. Additional or extended QoS classes will be necessary to handle TSN traffic in a 5G network.

V. CONCLUSION

This paper gives an overview of ongoing standardization activities in 3GPP on the topic of the integration of 5G and TSN for future industrial communication infrastructures. Several issues and open topics related to the requirements on an integrated industrial network have been discussed. Beyond these, there is a number of other important topics that have to be considered yet (e.g. configuration or security).

In the bigger picture, introducing new vertical applications and corresponding requirements like URLLC into 5G brings together communities with different mindsets, assumptions and expectations. In this case, there is the point of view of “integrating 5G as a new technology into TSNs” and the point of view of “adding TSN functionalities in 5G networks”. The opportunity to reconcile these different mindsets is given by organizations like the 5G ACIA, promoting dialog between relevant stakeholders from operational technology (OT) industry and information and communications technology (ICT) companies.

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