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Synchronization Requirements of Converged Wired and Wireless Time-Sensitive Networks

Maximilian Schüngel, Steven Dietrich, Shun-Ping Chen[†], Michael Kuhn[†]
Bosch Rexroth AG, [†]Darmstadt University of Applied Sciences
maximilian.schuengel@boschrexroth.de

Abstract: Following the trend of Industry 4.0, future factory automation will introduce an increasing number of mobile applications to enable the desired highly flexible production. Novel challenges arise for the underlying communication system. This includes the coexistence of real-time and non-real-time communication while supporting mobility. A promising solution is the integration of Time-Sensitive Networking (TSN) and the fifth generation cellular network technology (5G). A key aspect of real-time communication is the establishment of a common sense of time for the aspired fast and precise applications. This work covers industrial use cases of novel TSN/5G networks. An overview on related industrial use cases is given followed by a detailed description of selected uses cases and their communication requirements. This work concludes with a feasibility assessment of the selected use cases, with a strong focus on the synchronization. Possible benefits of novel TSN/5G networks are shown and current shortcomings are discussed.

1 Introduction

A current subject of the industry and academia is the unification of communication technologies to develop a single technology that is able to satisfy the diverse requirements raised by different industrial applications. The integration of Time-Sensitive Networking (TSN) and the fifth generation cellular network technology (5G) is a promising solution. It is currently discussed by the respective standardization groups IEEE and 3GPP. The 5G/TSN convergence is discussed to be transparent such that the integration of 5G into an existing TSN network is seamless. Therefore, the 5G system (5GS) introduces boundary TSN translator devices which are responsible to conceal the 5G complexity from the TSN network [5G-21].
A prerequisite for industrial applications and real-time communication is a tight synchronization in the time domain. The synchronization in TSN networks is established

through the generalized Precision Time Protocol (gPTP) according to IEEE 802.1AS. A major challenge of integrated TSN/5G networks, with respect to traditional TSN networks, is to achieve and maintain tight synchronization between end devices. This is because the convergence of TSN and 5G yields the engagement of heterogeneous synchronization mechanisms [S+21] and because the deployment of radio links introduces uncertainty.

Use cases of integrated TSN/5G networks are heavily discussed and the performance of the individual technologies, i.e. TSN and 5G, is evaluated. However, there are not many studies on the actual End-to-End (E2E) performance of integrated TSN/5G networks. The use cases are often discussed against inconsistent performance indicators. This work studies use cases of factory automation, discusses their E2E requirements which are mapped to a consistent set of performance indicators, and assesses the feasibility of novel TSN/5G networks for such use cases.

2 Performance Indicators of Industrial Communication

Factory automation comprises various different applications that are generally more demanding than other classes of industrial applications. Consequently, the requirements on the underlying communication are more challenging. In order to discuss the feasibility of factory automation applications from a communication perspective, key performance indicators (KPIs) have to be defined.

For both wired and wireless industrial networks KPIs are known from the literature. As main contributor for wired industrial communication the group of IEC 61784 standards provides nine different KPIs in total. The most relevant KPIs for factory automation applications are the delivery time (or latency), the synchronization accuracy, and the real-time (RT) throughput. In scope of this work the synchronization accuracy refers to the maximum time deviation between two independent clocks, i.e. from an E2E perspective. This is different to the synchronization accuracy that describes the maximum time deviation of a clock towards the reference clock as often used in the literature.

Different to wired communication, wireless communication involves uncertainties due to the usage of a shared transmission medium. To discuss the feasibility of factory automation applications in regard to converged wired and wireless networks, i.e. TSN/5G networks, additional KPIs have to be defined in order to account for the wireless communication part. Typical KPIs known from the literature are the availability (or packet loss rate), the number of nodes, the service area, and the node mobility [5G-19, F+14]. The combination of the discussed KPIs for both wired and wireless communication yields the following KPIs for TSN/5G networks:

- Latency
- Synchronization accuracy
- Payload
- Cycle time
- Packet loss rate
- Number of nodes
- Service area
- Mobility

3 Overview of Use Cases in Factory Automation

Factory automation is concerned with discrete production processes that are diverse and include various different applications itself. The manifold applications can be grouped in three different use case areas. The grouping is based on the type of application and the imposed requirements referring to the previously discussed KPIs. The following use case areas can be identified for factory automation [3GP21, 5G-19]: 1) Motion control, 2) Control-to-control, and 3) Mobile robots.

These use case areas are discussed briefly in the following section. A consolidated collection of requirements for the different use case areas and their subordinate use cases is given in Tab. 1. The provided collection of requirements was gathered from related literature and research studies.

Motion control is a specific application of closed-loop control. To control a physical process with high precision, fast control loops are required which exchange target and actual values between controller and actuators/sensors. The communication between the motion controller and both actuators and sensors follows a cyclic pattern with deterministic constraints. Motion control is the most challenging use case area in factory automation and thus imposes the most stringent requirements on the underlying communication [5G-19]. It is associated with the field level of the automation pyramid [Nof09] and relies traditionally on Industrial Ethernet (IE) or legacy fieldbus technologies. Popular motion control use cases are printing machines (control-to-device, C2D), machine tools, packaging machines, and robotic motion control [3GP21, 5G-19, Bro18, D+17, F+14].

Control-to-control use cases refer to applications that involve multiple machines or subsystems. Each machine or subsystem deploys a dedicated controller. Control-to-control use cases apply either to large machines which cluster individual machine functions into different subsystems or to distributed applications which includes multiple individual machines [3GP21]. Since the different machines or subsystems influence a joint process, they are required to perpetually communicate. The communication is cyclic and is exposed to deterministic constraints similar to the motion control use cases but relaxed. Control-to-control use cases naturally refer to the control level and typically rely on IE technologies. Control-to-control uses cases known from the literature are printing machines (control-to-control, C2C) and assembly lines [3GP21, 5G-19].

Mobile robots use cases involve any kind of mobile machinery, e.g. Autonomous Guided Vehicle (AGVs), that are deployed on the factory floor. Mobile robots can be viewed as individual machines that elaborate a process while having degrees of movement. In context of factory automation, mobile robots are predominantly used by means of AGVs for transportation and logistic purposes. Mobile robots implement a dedicated controller for basic functionalities and are typically controlled by a centralized guidance control system which provides missions and routes [5G-19]. Mobile robots continuously communicate with the central guidance control system. They provide their current location with a high precision on the basis which the guidance control system adapts missions and routes. The communication is again based on a cyclic pattern with deterministic properties but shows relaxed requirements compared to the previous use case areas. Challenging use cases of mobile robots are cooperative carrying applications and video-operate remote control [3GP20, 3GP21, Bro18].

Table 1: Consolidated requirements of factory automation use cases [3GP20, 3GP21, Bro18, D+17, F+14, Kip01]

Use Case Area	Use Case	Latency	Synchronization Accuracy†	Payload	Cycle Time	Packet Loss Rate	Number of Nodes	Service Area	Mobility
1.	Printing Machine (C2D)	2 ms	0.25 µs–1.25 µs	20 B	2 ms	10^{-4}	100	25 × 25 m	14.4 km/h–72 km/h
	Machine Tool	0.5 ms	2 µs	50 B	0.5 ms	10^{-4}	20	15 × 15 m	72 km/h
	Packaging Machine	1 ms	10 µs	40 B	1 ms	10^{-4}	50	10 × 5 m	72 km/h
	Robotic Motion Control	0.5 ms	1 µs	50 B	0.5 ms	10^{-4}	50	50 × 10 m	72 km/h
2.	Printing Machine (C2C)	10 ms	0.25 µs	1 kB	10 ms	10^{-4}	10	100 × 30 m	stationary
	Assembly Lines	50 ms	2 µs	1 kB	50 ms	10^{-4}	10	100 × 30 m	stationary
3.	Cooperative Carrying	0.5 ms	500 µs	250 B – 500 B	1 ms	10^{-4}	100	1 km²	6 km/h – 12 km/h
	Video-operated Remote Control	10 ms	5000 µs	15 kB – 150 kB	10 ms	10^{-4}	100	1 km²	50 km/h

† end-to-end (E2E)

In the remainder of this section three particular use cases are discussed in detail. The use cases of 1) robotic motion control, 2) printing machines, and 3) cooperative carrying were selected because they impose stringent requirements on the underlying communication with special emphasis on the synchronization accuracy.

3.1 Use Case 1: Robotic Motion Control

Robotic motion control is a major topic of factory automation. Industrial robots elaborate a magnitude of relevant tasks such as assembly, machining, painting, pick and place, or welding. For such tasks, industrial robots have to support a large degree of motion using multiple axes and joints in order to handle complex processes. As discussed in Sec. 3 motion control refers to a closed-loop control process including a controller, actuators and sensors. Sensors may be placed anywhere on the robot and such also onto moving parts. In such cases a physical connection for communication is cost intensive, prone to errors, and typically lacks the support of high data rates [D+17]. To overcome these issues, sensors like a high resolution camera may be connected wirelessly. In this work we additionally assume that the robot represents an enclosed system for modulartiy and flexibility. It includes a controller, a Programmable Logic Controller (PLC), and its connected field devices, i.e. sensors/actuators.
The E2E synchronization requirement of 1 µs between its field devices yields an precision of 20 µm considering a maximum movement speed of 20 m/s. This is really competitive e.g. when compared to pick and place machines which achieve a similar accuracy but typically rely on wired communication. As discussed before, the robot is assumed to be an enclosed system. It may be a subsystem of a large machine or conglomerate of machines such as an assembly line. Therefore, it is assumed that both the robot PLC and the wireless sensors are connected to the 5G RAN using dedicated

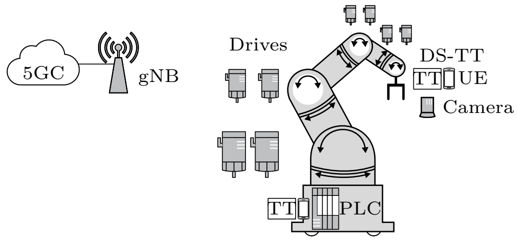

Figure 1: Robotic motion control: Closed-loop motion control that uses wireless sensors for the feedback loop.

User Equipment (UEs) and Device-Sided TSN Translators (DS-TTs). Fig. 1 illustrates an exemplary deployment for the given use case. A local PLC connects field devices via a line/ring network. Additionally, a high resolution camera, serving as exemplary wireless sensor, is mounted on the robot (on a moving segment).

3.2 Use Case 2: Printing Machine

Printing machines are large machines that are used to produce large batch sizes of e.g. newspapers or packaging. They consists of multiple subsystems which cluster different machine functions. For instance flexography or offset printing systems use dedicated printing units that are associated with dedicated colors. The superposition of the different colors yields the final image. Each printing unit represents a subsystem. Thereby printing machines become cross domain. At field level, i.e. within a subsystem, the specific machine functions can be classified as motion control use case. At control level, i.e. between different subsystems, the higher-level application represents a control-to-control use case.
A deviation of 5 µm results in a blurry image with visible artifacts. Assuming that the substrate, e.g. paper, moves with a speed of up to 20 m/s through the printing machine, the different printing units have to be synchronized within less than 0.25 µs E2E [D$^+$17]. In return this means that the printing units have to be synchronized to the reference point with a synchronization accuracy of 0.125 µs. A more sensible substrate speed is 4 m/s which is typically used for offset or flexography printing machines [Kip01]. Such a reduced substrate speed then requires a synchronization accuracy of 0.625 µs of the individual printing units. Printing machines expose a large spatial extent of up to 100 m $\times$ 30 m and include up to 10 different subsystems [3GP21]. A subsystem itself may consist of up to 100 devices [3GP20, Bro18]. The typical distance between access points (APs)/radio dots (RDs) in factory deployments is 30 m. Based on that about 3 APs/RDs are required to provide coverage for the printing machine.
As discussed before, a printing machine clusters machine functions into different subsystems. Each subsystem implements a dedicated controller, a PLC, which is responsible to control its associated machine function. On a superordinate level, a printing machine uses a Supervisory PLC (S-PLC) to coordinate the different subsystems. Due to the stringent communication requirements, printing machines traditionally rely on

IE technologies [5G-19]. At field level, i.e. within a subsystem, and at control level, i.e. between subsystems, line networks are established for cost efficiency purposes and a reduced management effort. For redundancy the line networks are typically being closed to ring networks. Fig. 2 shows an exemplary deployment of integrated TSN/5G networks with a printing machine. At control level the wired links between the S-PLC and the PLCs of the different subsystems are replaced by wireless links. The traditional line/ring networks are transformed in a star network which are typical for wireless technologies. The S-PLC is located at a central location and is connected to the 5G Core (5GC) via a Network-Side TSN Translator (NW-TT). The different subsystems implement a UE and DS-TT each. At field level the subsystems still leverage wired links, i.e. TSN. The integration of TSN/5G networks yields many possible benefits. At control level the machine deployment becomes highly flexible with a facilitated reconfigurability. This is supported by the self containment of subsystems which still rely on wired technologies. From a practical perspective this means that subsystems can easily be added/removed, e.g. special effect colors. Deploying the S-PLC in a central location decouples the supervisory control from the actual machine functions enabling a virtualization which promises future proof and scalability [5G-21].

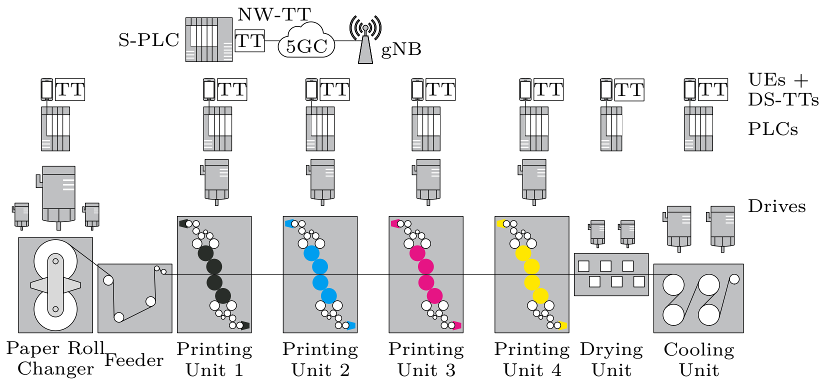

Figure 2: Printing machine: Modular architecture that connects subsystems via 5G.

3.3 Use Case 3: Cooperative Carrying

In factory automation mobile robots are often used for transportation and logistic applications. Special purpose mobile robots for such applications are AGVs. AGVs move along predefined paths through the factory floor. The paths are calculated and provided by central guidance control system. During operation the AGVs continuously monitor their current location using various sensors such as cameras or Radio Frequency Identification (RFID) technology. They provide their current location to the guidance control system on the basis which it can adopt the calculated paths in order to prevent collisions.

Collaborative AGVs move at a speed of 6 km/h to 12 km/h during the cooperative car-

rying operation. A synchronization accuracy of 250 µs to a reference point [3GP21], i.e. the guidance control system, which is derived as 25 % of the cycle time [3GP21], yields a precision of 0.83 mm to 1.66 mm of the collaborative movement. The cooperative carrying operation involves up to 8 AGVs simultaneously. It occurs in a service area of up to 1 km^2 [3GP20, 3GP21] which comprises up to 100 AGVs [3GP21].
AGVs implement a local PLC that is in charge for the actual motion control and safety functions. Within an AGV different systems such as actuators and sensors are connected to the local PLC. For simplicity a line/ring network is assumed as industrial practice. A switched network may also be conceivable. As mentioned before, AGVs require a guidance control system for mission and path planning. The guidance control system is typically located in a central location similar to the S-PLC of a printing machine. Fig. 3 shows a representative cooperative carrying application leveraging integrated TSN/5G networks. Two AGVs carry a difficult work piece that is too large and heavy to be carried by a single AGV. The AGVs local PLCs are connected via a dedicated UE and DS-TT to the 5G RAN. The guidance control system, here represented as S-PLC, is connected to the 5GC via a NW-TT.
The benefits of using integrated TSN/5G networks over other technologies such as Wifi6 lies in the ultra reliability and ultra low latency profile of 5G in conjunction with the RT interface provided with TSN. The short cylce times and the high synchronization accuracy allows novel collaborative processes with high precision. With the spectral efficiency of 5G more AGVs can be deployed in parallels on the factory floor.

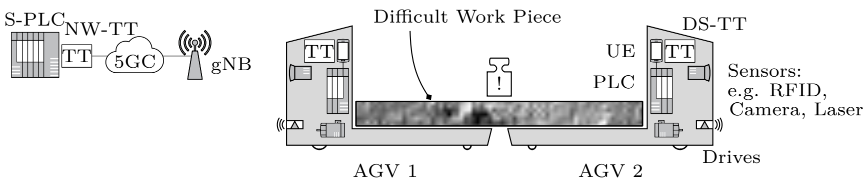

Figure 3: Cooperative carrying: Multiple AGVs collaborate to carry a work piece.

4 Assessment of Use Cases in Factory Automation

As discussed in Sec. 1 integrated TSN/5G networks involve heterogeneous synchronization mechanisms. From an E2E perspective gPTP is the fundamental synchronization mechanism. In PTP based synchronization a grandmaster (GM) clock provides its reference time to the remaining clocks in the network. Our assessment of integrated TSN/5G networks is based on [S^+21]. This study researches different GM deployment scenarios in integrated TSN/5G networks and evaluates their E2E performance. The study distinguishes three distinct GM deployment strategies. First, a network-sided GM which is the state-of-the-art approach and specified in Rel. 16. It refers to a GM that is connected to the 5GC. Second, is a device-sided GM which is part of the ongoing Rel. 17 specifications. It refers to a GM that is connected to the 5G RAN. And third, is a 5G-sided GM which is a novel strategy proposed in [S+21]. It refers to a scenario where the 5G system itself serves as a GM and provides its reference time the both network- and device-sided devices.

4.1 Use Case 1: Robotic Motion Control

As discussed in Sec. 3.1 and shown in Tab. 1, the robot motion control use case requires a stringent E2E synchronization accuracy of 1 µs implicating that device clocks may deviate 0.5 µs from the GM clock. For the robotic motion control use case it is critical that the PLC and the field devices, such as wireless sensors, are tightly synchronized. As discussed before, both devices are connected to the 5G RAN using a dedicated UE and DS-TT. According to [S+21] the 5G-sided GM deployments is capable of synchronizing device-sided device with a worst-case accuracy of 0.44 µs or 0.37 µs for a subcarrier spacing of 60 kHz or 120 kHz respectively, and thus is able to support the robotic motion control requirements from a synchronization perspective. However, the estimations from [S+21] use a rather pessimistic paramterization of the clock properties. When more realistic parameters are used from a practical point of view, more deployment options become feasible. We use relaxed parameterization that is a timestamp granularity of 8 ns, a link propagation delay of 50 ns which is equivalent to a 15 m wired link [G+17]. Then a 5G-sided GM deployment achieves a worst-case synchronization accuracy of 0.46 µs, 0.34 µs, or 0.27 µs for a subcarrier spacing of 30 kHz, 60 kHz, or 120 kHz respectively. In addition the state-of-the-art network-sided GM deployment is now able to support the synchronization requirements with an accuracy of 0.45 µs or 0.38 µs for subcarrier spacing of 60 kHz or 120 kHz respectively.

4.2 Use Case 2: Printing Machine

As discussed in Sec. 3.2 and shown in Tab. 1, printing machines impose among the most stringent communication requirements especially in regard to the synchronization accuracy. As elaborated printing machines require its field devices, i.e. drives within a printing unit, to be synchronized within 0.125 µs to 0.625 µs in reference to the S-PLC in order achieve an E2E synchronization accuracy of 0.25 µs to 1.25 µs.
According to [S+21] a 5G-sided GM deployment is able to achieve an E2E synchronization accuracy between S-PLC and subsystem PLC of 0.62 µs or 0.55 µs for a subcarrier spacing of 60 kHz or 120 kHz respectively. A state-of-the-art network-sided GM, where the S-PLC serves as GM, achieves a E2E synchronization accuracy of 0.62 µs for a subcarrier spacing of 120 kHz. However, this leaves not much head room for synchronizing field devices that are connected to the subsystem PLC. Using a relaxed paramterization as elaborated in Sec. 4.1 creates enough head room for synchronizing field devices with the required precision. Fig. 4 represents the synchronization accuracy of field devices connected to the subsystem PLC over different subcarrier spacings and for different GM deployments. On the left the network-sided GM deployment is shown where the S-PLC serves as GM. On the right the 5G-sided GM deployment is shown where the S-PLC and the field devices are synchronized equally by the 5G system. As expected the 5G-sided GM deployment performs best and is able to synchronize up to

3, 9, or 13 field devices, which are connected in a line network to the subsystem PLC, with the required precision of 0.625 µs. When ring networks are established at field level, then up to 5, 17, or 25 field devices can be supported beyond the PLC.

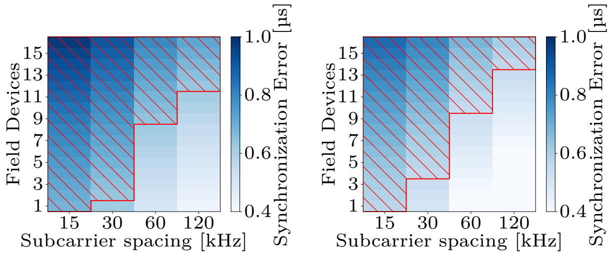

Figure 4: Assessment of E2E synchronization accuracy for printing machines: Network-sided GM (left) and 5G-sided GM (right). The hatched area indicated where the worst-case E2E synchronization error exceeds 0.625 µs.

4.3 Use Case 3: Cooperative Carrying

As discussed in Sec. 3.3 and shown in Tab. 1, the cooperative carrying use case imposes relatively relaxed requirements regarding the synchronization accuracy. The cooperative carrying use case requires the AGVs to be synchronized E2E within 500 µs in order to achieve a precision of 0.83 mm to 1.66 mm. This yields a maximum deviation of 250 µs for the AGV clocks towards the GM clock, e.g. the guidance control system. According to [S+21] the synchronization accuracy requirements imposed by the cooperative use case can easily be achieved with integrated TSN/5G networks even under worst-case parameterization. Using a network-sided GM, e.g. the guidance control system, AGVs can be synchronized with a worst case E2E synchronization accuracy of 0.88 µs, 0.81 µs, 0.69 µs, or 0.62 µs for a subcarrier spacing of 15 kHz, 30 kHz, 60 kHz, or 120 kHz respectively. This means that the speed of movement of the collaborative AGVs can be easily increased at least from a synchronization perspective.

5 Conclusion and Future Work

In this work we derived key performance indicators to classify different use case areas of factory automation. We provided a collection of use cases and their requirements in reference to the key performance indicators. We described a selection of use cases in detail highlighting their networks and application specific synchronization requirements. We compared the use case requirements with a study of heterogeneous synchronization mechanisms in integrated TSN/5G networks and assessed their feasibility.
Both robotic motion control and printing machine use cases impose stringent synchronization accuracy requirements. However, in reference to the emphasized study it becomes evident that both use cases can be implemented using integrated TSN/5G networks when a more sensible parameteriztation is assumed than originally presented

in the study. Important for the implementation of such cases is the grandmaster selection and the 5G subcarrier spacing configuration. The cooperative carrying use case easily can be implemented with TSN/5G networks even using the state-of-the-art network-sided grandmaster deployment and the worst-case parameterization as presented in the reference study.
For our future work we plan to further collect more relevant use cases. Since the assessment of the shown use cases is based solely on a single study from a single reference, we plan to elaborate real-world measurements as soon as Rel. 16 networks and equipment becomes available. First preliminary measurements already confirmed the potential of integrated TSN/5G networks.

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