Digital Twins of Industrial and 6G Systems: Enablers Towards Situational Awareness

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***Abstract*—This paper highlights the value of Digital Twins (DTs) in optimizing and maintaining Cyber-Physical Systems (CPSs) across domains like manufacturing and communication. It proposes the interaction between an industry DT and a 6G DT and identifies Situational Awareness (SA) as a key step toward supporting critical services. A use case involving 6G communication with mobile User Equipment (UE) in manufacturing is analyzed to identify critical operating scenarios and how SA can predict and mitigate the risk of failure in these scenarios. Based on this use case, relevant parameters for improving the SA of the entire CPS are identified in both DTs and an example of interaction is given for optimizing the joint task planning and execution. Additionally, the benefits of cross-domain SA are demonstrated through 5G testbed measurements. The use case illustrates the broader applicability of our proposal.**

***Index Terms*—6G, Digital Twin, Situational awareness, Industrial communication, Safety-critical communication, 5G testbed measurements**

I. Introduction

In recent years, the concept of network DTs has received increasing attention from the research community in the context of mobile networks like 5G but also for upcoming 6G systems. Network DTs comprises information about devices and traffic flows, network load, network connectivity characteristics, and other relevant parameters. Such state information is fed to the DT continuously either through collecting the information from the network or through explicit services, for instance, with respect to sensing functionality of devices. While DTs have arguably existed already for a long time in networked systems, for instance as an information base to run a network operation center, network DTs are recently recognized due to their value for application layer services, as well as for AI-implementations targeting ultimately network (and application) optimization [1]–[4].

Since the advent of 5G networks, industrial automation has been a key application area for current and future mobile networks. Such applications are characterized by strict latency and reliability requirements, which led to the specification of Ultra-Reliable Low Latency Communication (URLLC) services in 5G. 6G will enhance the capabilities of 5G and will bring further benefits into the Industry 4.0 perspective, such as connectivity between the physical system and the DT, positioning and sensing information about the physical environment, and computing capabilities via edge computing [4]. A particularly important use case in this context is adaptive manufacturing, which has become prominent in industrial automation and production in recent years. Adaptive manufacturing facilitates quick changeover times, enhancing overall operational agility [5]. Wireless communication can support these quick changeovers by removing the need for complex and cumbersome cabling and providing connectivity for mobile assets. However, it also introduces challenges due to the inherent stochastic nature of the wireless channel, which can lead to nondeterministic behaviour. Factors such as fluctuating signal strength, interference, physical obstacles in the transmission path, varying data traffic load and varying distances between transmitters and receivers can cause fluctuations in data transmission, leading to Packet Delay Variation (PDV) and reduction of Throughput (TP), which can undermine the efficiency of manufacturing processes. The variability of latency can disrupt the precise timing required for automated processes, resulting in production errors and inefficiencies. These issues are particularly critical in functional safety applications where higher latency triggers safe-state measures and increases downtime, as shown in [6]. In these scenarios, future mobile networks would benefit from a proactive approach to identify and mitigate situations with performance degradation. DTs can enable this proactivity. However, despite technological progress, there is still a gap in the ability to demonstrate their practical usability at scale. Specifically, real-world implementation and showcases of benefits remain limited. Additionally, further work is needed to define a standardized and comprehensive approach and set of parameters from the physical network that enable comprehensive mirroring in the digital twin.

In contrast to the use of DT technology in networking, automation systems have leveraged DTs commercially for quite some time. A typical CPS in automation contains multiple subsystems. Thus, its DT is composed of the DTs of those subsystems. A frequently applied standard in this context is Reference Architectural Model Industrie 4.0 (RAMI 4.0), which is utilized to structure essential areas by integrating IT, manufacturing, and product lifecycles. This architectural model includes physical devices encapsulated through an Asset Administration Shell (AAS) concept [7]. AAS is a standardized digital representation of a physical or logical asset. The AAS consists of a number of submodels in which all the information and functionalities of a given asset, including its features, characteristics, properties, statuses, parameters, measurement data and capabilities, can be described. It provides structured and interoperable interfaces that enable seamless data exchange, integration, and communication between assets and systems across different vendors and platforms. The AAS encapsulates all relevant information and functionalities of an asset throughout its lifecycle, supporting automation, monitoring, and control in industrial environments.

These assets function as core Industry 4.0 components, forming the foundation for DTs in industrial CPS. Thus, for smart factories, RAMI 4.0 offers an universal framework for managing asset-related data and functions. Through these DTs, it becomes possible to create an accurate digital representation of the manufacturing process and Operational Technology (OT) systems.

The discrepancy in the maturity of usage of DT technology in automation systems and in networked systems, paired with the need for a higher degree of predictability in future networked systems, opens the challenging question of how to design and operate such integration in the 6G context. Which architectures will emerge that enable data exchange between various DTs of industry and network domain? What type of trade-offs exist with respect to different degrees of integration? And which gains can be achieved, given these different degrees of integration? In this paper, we first identify the concept of SA as crucial towards the integration of different DTs. Our main contribution is a discussion of co-designed cross-domain collaboration and optimization between an industrial OT system and a 6G network, exemplified through a use case from industrial automation and backed up with 5G testbed measurements on a factory floor. To this end, we investigate how DTs can be used, what parameters they require and what interactions are desirable.

The rest of the paper is structured as follows: the concept of SA, DT and interacting DTs are provided in Sec. II; the use case description, critical operating scenarios and benefits of SA for both domains are explained in Sec. III; an example of possible interaction flow and verification of SA benefits through the 5G testbed measurements are provided in Sec. IV; conclusions are drawn in Sec. V.

II. SITUATIONAL AWARENESS VIA DIGITAL TWINNING CONCEPT

Digital Twins (DTs) are computer-based models that emulate, simulate, or mirror the behavior and lifecycle of a corresponding physical entity [8]. DTs are linked to their physical counterparts and must have certain essential characteristics. First, an appropriate data structure is required to represent the real-world state and knowledge at a detailed level suitable for the scenario, from low-level hardware to aggregated characteristics of services and networks. Second, there must be continuous synchronization between the real world and the twin, allowing them to evolve in parallel [9]. Typically, the main data flow consists of measurements and events from the real-world asset to the twin necessary for characterizing performance and behavior. Configurations and control actions can also be sent back to the real world using suitable control mechanisms [1]. They enable optimizing or planning possible system modifications with "what-if" analysis and applying tools for predictions or simulations. This can lead to SA and automated system configurations or recommendations for system changes.

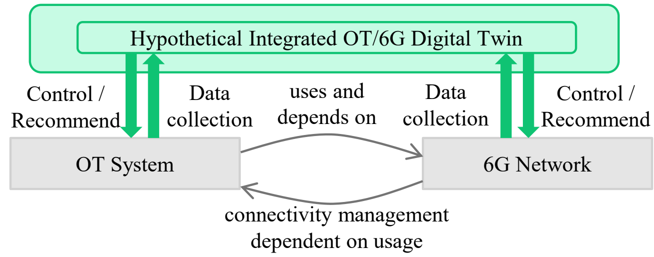


Fig. 1: Theoretically optimal CPS with joint OT - 6G optimization

SA has at first been investigated with respect to human dynamic decision-making in various domains. It has different definitions, but the most commonly used one is by Endsley: *"The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"* [10]. If this definition is applied to the 6G network or on the entire CPS, the three main steps towards obtaining the SA are perceiving or sensing the environment and the system behavior, analyzing the collected data to understand the current state, and finally, projecting the future state of the CPS. The projection is then fed to the decision-making logic and the results of consequent actions are fed back to the following SA analysis. Considering the computation capabilities that exist nowadays and continuous advancements in Artificial Intelligence (AI) technologies, it is the right time to bring SA into the 6G System (6GS) and the CPS.

To improve the resilience of the 6GS and factory operations, we propose the use of DTs for both OT and 6G systems, not only for individual optimizations within their respective domains but also for interactive coordination to gain and utilize SA on both sides. In an industrial scenario, these two systems are not independent from an operational standpoint. Operational changes in the manufacturing process in a factory will affect the network and vice versa. For this reason, we propose allowing active interactions between the systems, which enables joint planning and execution of new tasks. We suggest that such novel interactions are raised to the DT level, where every task could be evaluated in many different scenarios and configuration options without affecting the ongoing processes.

Conceptually, a joint optimization of the operations of the CPS would yield the best results, as shown in Fig. 1. However, the OT system of a factory and the 6GS belong to different domains and a separation of concerns is advised. This may be motivated by, e.g., privacy concerns about what detailed information from within one system is shared externally,

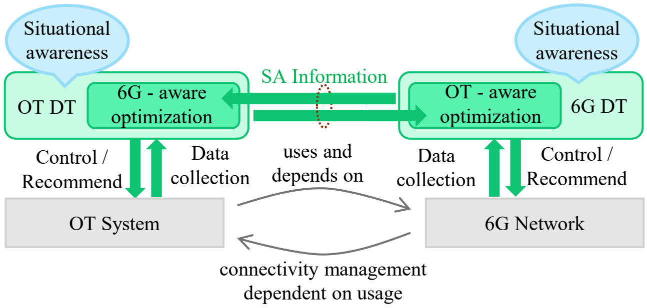


Fig. 2: CPS optimization with mutual situational awareness. Separation of concerns scalable design

but also by scalability and the flexibility of independence (e.g., acknowledging that development lifecycles in different domains can differ significantly). To still allow for mutual optimization, we propose an interaction model between the DTs, as shown in Fig. 2. Each DT is synchronized to its corresponding physical system and receives system-related data. The DT can also control or configure the physical system or provide recommendations to the (embedded controller of the) physical system. For a 6G DT, the interactions with the network can utilize network exposure Application Programming Interfaces (APIs) [11]. Interactions between the different DTs comprise the exchange of contextual data and can be based on AAS, which allows interoperability among different subsystems [7], [11]. This data is in the form of SA information rather than raw data. Still, the information needs to reveal the mutual influence of the two systems on one another and allow for enhancing the reliability and agility of the CPS as a whole. Individual DTs have access to vast amounts of data. Nevertheless, the collection of context and situational information should not be excessive but should rather be focused and motivated by a purpose and value that this information can provide to the other domain (and DT). In this way, optimizations can be made, where the OT system becomes aware of and considers the 6GS in its operation planning, and vice versa, as shown in the Fig. 2. Various sensors are integrated into the machinery and also the factory floor environment. CPS subsystems often rely on precise positioning, Light Detection and Ranging (LiDAR) sensors and visual sensors such as cameras that can be fixed, installed for surveillance, or mobile, deployed as a part of Automated Guided Vehicles (AGVs), temperature sensors, light curtains, etc. Furtheron, the sensing data from Supervisory Control and Data Acquisition (SCADA), surveillance/security systems and fleet managers is collected by the Operational Technology DT (OT DT) and translated to SA, which is used then to enhance, e.g., AGV navigation and production optimization. Although the 6G network is a separate subsystem of the CPS, sensed data and the situational information available at the OT DT can provide valuable information for the 6G DT. The 6G DT itself generates SA for communication services from a different set of parameters that it receives from the 6GS such as radio resource usage, network coverage, provided Quality of Service (QoS), service availability, etc [12]. The OT DT can benefit from such 6GS information, e.g., in its task planning. In addition, further SA information can be provided by the 6GS to the OT DT, such as localization or sensing data obtained via the 6G positioning or Integrated Communication And Sensing (ICAS). SA can provide a broad set of information that can establish contextual information to be shared with another domain DT. Based on the critical operating scenarios of the use case discussed later in this paper, we focus on resource, radio, and traffic awareness.

III. Use case analysis

To motivate the benefits of SA and interaction between OT DT and 6G DT we analyze a cooperative AGV use case from [5]. The use case describes a joint task of two collaborative and virtually coupled AGVs. As illustrated in Fig. 3, the AGVs circled in red, together carry an object through different safety-critical zones to the processing cell and further to the storage area. Depending on the enclosure level, i.e., human accessibility, the different zones have different safety and communication requirements. In the processing cell, stationary robots operate on the object itself and communicate with AGVs for precise object orientation and positioning, thus demanding lower communication latency and increased TP and reliability. This use case implies high mobility of UEs and dynamically changing traffic patterns in the wireless communication network. The 6GS needs to select features and configurations, such as robust transmission modes and enabling fast channel access for time-critical traffic, e.g., via configured grant access, that provide reliable low latency communication [13], [14], [15]. However, in this use case, the traffic requirements of UEs change depending on their tasks and position on the factory floor. Awareness about current and planned tasks and movements of the UEs provides additional information to the 6GS that can help in planning future resource allocations to fulfill the required QoS for all UEs.

A. *Critical operating scenarios*

Under the assumption that proper radio planning has been performed and the 6G network is designed to support the communication requirements, we can focus on only a few critical operating scenarios that may stress the network's capabilities.

One possible critical scenario in the use case is the clustering of UEs. Assuming a large number of UEs on the factory floor, it is possible that they become clustered in a small area, saturating the radio cell's capacity, especially if this occurs at a location with poor radio link quality. As a result, the network may not be able to serve the next incoming UE, or the communication service may even be lost for currently served UEs. The second critical scenario is the navigation of UEs through an area with poor coverage. The signal coverage on the factory floor can vary significantly, depending on the radio network deployment and signal blockage due to obstacles. More radio resources are needed to maintain the promised QoS when UEs enter areas with weaker signal coverage. This

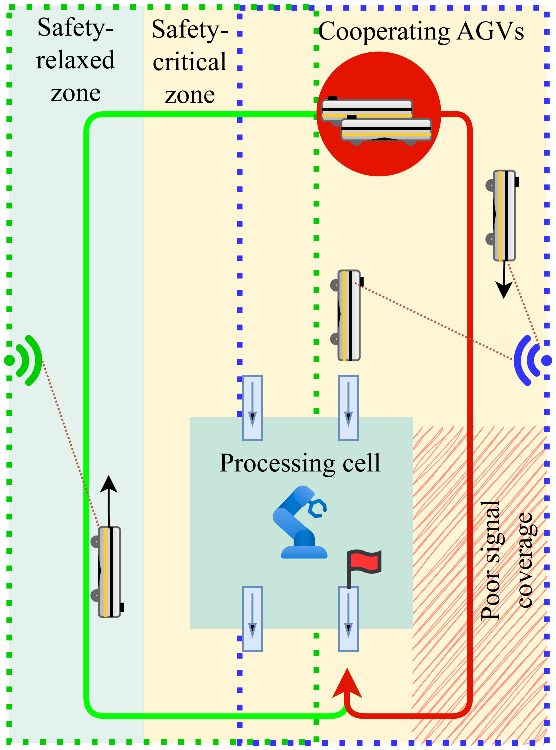


Fig. 3: Use case illustration

may lead to resource deficiency with the same consequences as in the first critical scenario.

The third critical scenario specific to this use case is a change of communication requirements depending on the position of the UEs. A lower latency is required when a UE moves from the safety-relaxed zone to the safety-critical zone, cf. Fig. 3. If the UE enters the processing cell, the required latency reduces even further and the TP rises. Thus, the 6GS must provision and plan its resources to cope with varying traffic patterns and apply radio resource management methods accordingly.

B. SA Benefits for the OT System

In the context of this use case, we aim to discuss how SA stemming from the 6GS can provide benefits for the OT system, as also shown in Tab. I.

Some processes in the OT system depend on the availability of reliable communication with the specified minimum QoS during process execution. When planning such a process, the OT system can benefit by knowing if the network can fulfill the communication need. To this end, it is beneficial for the OT system to consider the capacity or resource availability of the 6G network in different regions of the shop floor area. From that, it can judge which processes and how many processes can be supported by the network simultaneously at a particular location. It can plan the dispatching of OT processes accordingly by avoiding network overload as it will be shown later in this paper. Another possibility that the OT system can exploit is to utilize the flexibility that is provided by certain OT processes. As described in [5], some processes can support multiple modes of operation. For example, an AGV can operate at different velocities. At higher velocities, a faster control process is executed compared to an AGV at low velocity. This operation mode has a higher traffic load due to the higher frequency of the control cycles; at the same time, it requires lower latency due to the shorter cycle time of the control loop. As can be seen, different operation modes of OT processes may need different amounts of radio resources to be supported by the network. At the same time, these operation modes can differ in their productivity with regard to the OT production objectives. The OT task planner can plan and dispatch OT processes with appropriate operation modes to provide the highest OT productivity while staying within the capacity constraints of the 6G network infrastructure.

The SA that the 6G system can provide to the OT DT for this purpose is information about the available radio resources. This can be provided as a spatial map of the available remaining capacity in the 6G network and can be determined by considering the different radio cells, their radio propagation characteristics and the radio resource utilization of the existing communication services.

Different interaction models can be imagined between the OT DT and 6G DT. The 6G DT could determine a spatial network capacity map for the OT DT and provide updates whenever more significant differences in available capacity occur. The OT DT can also request capacity information from the OT DT for an OT process by specifying the traffic demand, QoS requirements, and location or path; the 6G DT can then provide according information on demand.

The establishment of SA information is based on various data sources. Table I provides an example set of information sources and a characterization of their nature. Some parameters are static and configured once, while others are dynamic and have their values changed at different intervals. Furthermore, the dynamic parameters can be obtained from services or Network Functions (NFs) or measured.

Example: Radio resource triggered SA

Figure 3 illustrates the scenario where the available communication resources are not sufficient to fulfill the communication requirements. The factory area is covered by multiple Transmission and Reception Points (TRPs), which are dedicated either to cell 1 or to cell 2, outlined with green and blue dashed lines and antennas, respectively. The blue cell 2 serves the UEs in the more demanding processing area and is expected to have more occupied resources than the green cell 1. For illustration purposes, we assume that cell 2 has 90 percent of available resources occupied, while cell 1 has only 50 percent occupied. The capacity depends on the number of serving UEs and their requirements as well as on the radio environment and the locations selected for the TRPs during the network planning and installation. At locations with large distances to TRPs or potential strong radio signal attenuation due to obstacles in the propagation environment, this can result in weak radio link quality and low capacity, which must be considered in the capacity analysis. This is illustrated in Fig. 3 by the red sketched corner. For a new task for the AGVs, the fleet manager by default picks the shortest possible path for them, highlighted with a red arrow in Fig. 3, which passes through cell 2. Without SA, path planning is performed at the OT DT based on navigation maps, information about AGVs battery status, docking station location, charging schedules, maintenance schedules, and the capabilities of each AGV. This ensures maximum utilization of the mobile fleet.

When SA information about the 6GS is provided to the OT DT, the fleet manager may prefer to select the AGV path depicted in green, which passes through cell 1, as it has more capacity available and a lower risk of communication failure due to overload.

C. SA Benefits for the 6G System

The 6GS has to support the communication needs of various OT processes. To this end, it must ensure that sufficient radio resources are available to cover the communication needs at the target locations, thereby supporting the traffic with the required service performance (e.g., latency and reliability). This task can be improved by SA information provided from the OT DT to the 6G DT, as shown in Tab. I. By being aware of upcoming communication needs and their location, the 6GS can plan for future resource needs. Different applications can have different QoS requirements. Some applications require best-effort performance and can tolerate temporarily lower TP; for other applications, minimum performance requirements need to be matched and sufficient radio resources need to be reserved. Through load balancing, some of the traffic can also be shifted between radio cells, potentially releasing the load on specific target cells. As some OT processes may apply different operation modes with varying communication needs throughout their progress, an assessment of the entire OT process should be made by the 6GS. If the 6GS determines that the total network capacity is insufficient to support all the planned OT processes, it is beneficial to notify the OT DT in advance so that contingency actions can be considered.

The data sources for establishing SA at the OT DT are listed in Table II. We assume that parameters related to factory operation are provided by the OT DT as it represents a trustworthy state of the factory operations.

Example: Traffic triggered SA

We can explain the benefit of traffic awareness in the considered use case. Due to different safety-critical areas and phases of the task, different AGV paths can demand different data traffic requirements in the form of TP, latency, message cycle rate, and reliability. Moreover, the data traffic requirements can change within the same path. Without SA, the UE would have to specify the maximum data requirements it needs or the exact ones as soon as they are required. For resource allocation in the 6GS, reservations can be made in advance to ensure resource availability at these critical points. To this end, the 6GS benefits from information about future traffic demands and resource requirements, including worst-case scenarios, to plan for future resource needs and potentially reserve resources for anticipated critical applications.

IV. Joint Task Planning 5G Use Case

The full implementation of 6G DT and its interaction with the OT DT is still to come. However, it is possible to test the explained benefits of joint task planning on the factory floor using an industrial 5G testbed and present our view of the interaction from the 6G DT side. Before executing the task, the OT physical twin sends a request to the OT DT to validate the intent. The OT DT can simulate different ways to execute the task and send multiple requests for analysis to 6G DT to obtain network situational information. Each analysis request can carry OT parameters listed in Tab. II for the same or different Area of Interests (AoIs). The AoI is represented with multiple longitude-latitude pairs that define a convex polygon [16]. With multiple AoIs, the OT DT can obtain network situational information for multiple navigation paths on the factory floor (Fig. 4 top part). The 6G DT utilizes received parameters from OT DT and parameters from the 6G network (Tab. II) to generate and return SA information in the form of, e.g., a capacity map for each AoI. Based on this feedback, the best execution scenario is suggested by the OT DT to its physical twin. During the task execution, the 6G DT can receive additional requests from OT DT with the same AoIs or different ones if OT DT is simulating path change. In these new requests, the 6G DT also receives updated parameters from OT and can provide SA with higher accuracy. If at a certain moment the SA indicates significant deviation from previous analysis for the same AoI, the OT DT can be informed to adapt to new changes on time (Fig. 4 lower part). The described interaction can lead to a higher number of simultaneously served Autonomous Mobile Robot (AMR)/AGV UEs on the factory floor due to SA-enhanced path selection. This is verified in the industrial 5G testbed.

A map of a fully operational factory floor generated from the LiDAR scan is shown in Fig. 5 with a Signal to Interference plus Noise Ratio (SINR) heatmap layer on top. The factory

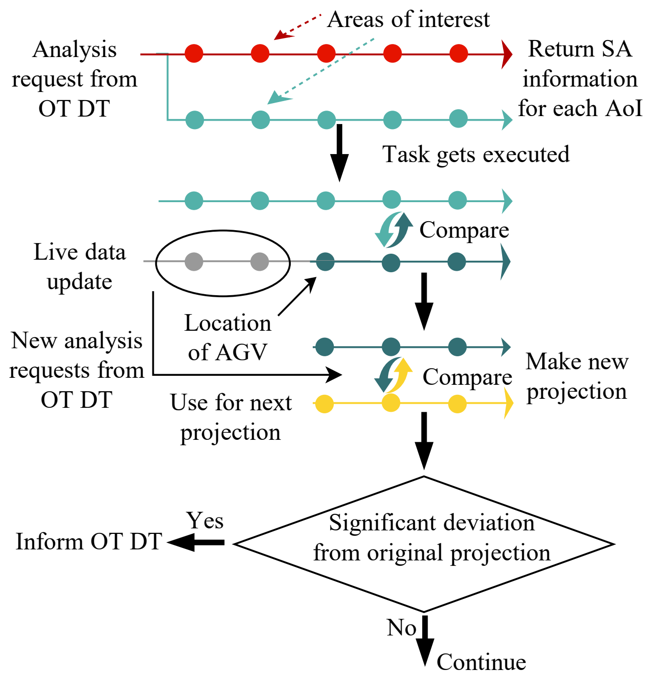


Fig. 4: 6G DT interaction with OT DT

TABLE I: SA information, benefits and actions

	SA source	SA destination	SA information	Action	SA frequency
Benefits for OT System	6G DT	OT DT	Spatial capacity map	OT plans and configures OT processes	SA information is refreshed whenever significant differences occur, or it is provided on request, e.g., for a specific path
Benefits for 6G System	OT DT	6G DT	Planned OT process requiring communication (time, location/path, traffic profile, QoS requirement). This can include different operation modes to be applied in different spatial zones	6G plans communication needs and may, e.g. reserve radio resources	SA information is refreshed whenever changes in the planned OT process occur

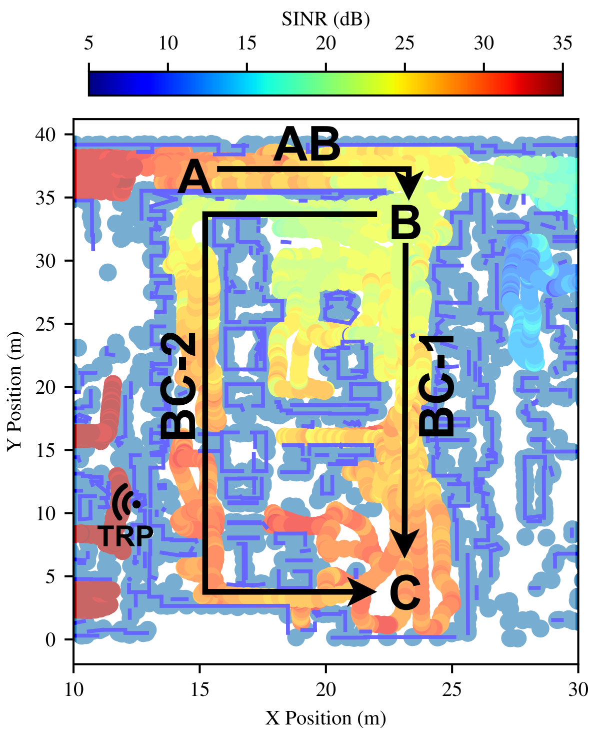


Fig. 5: Testing scenario

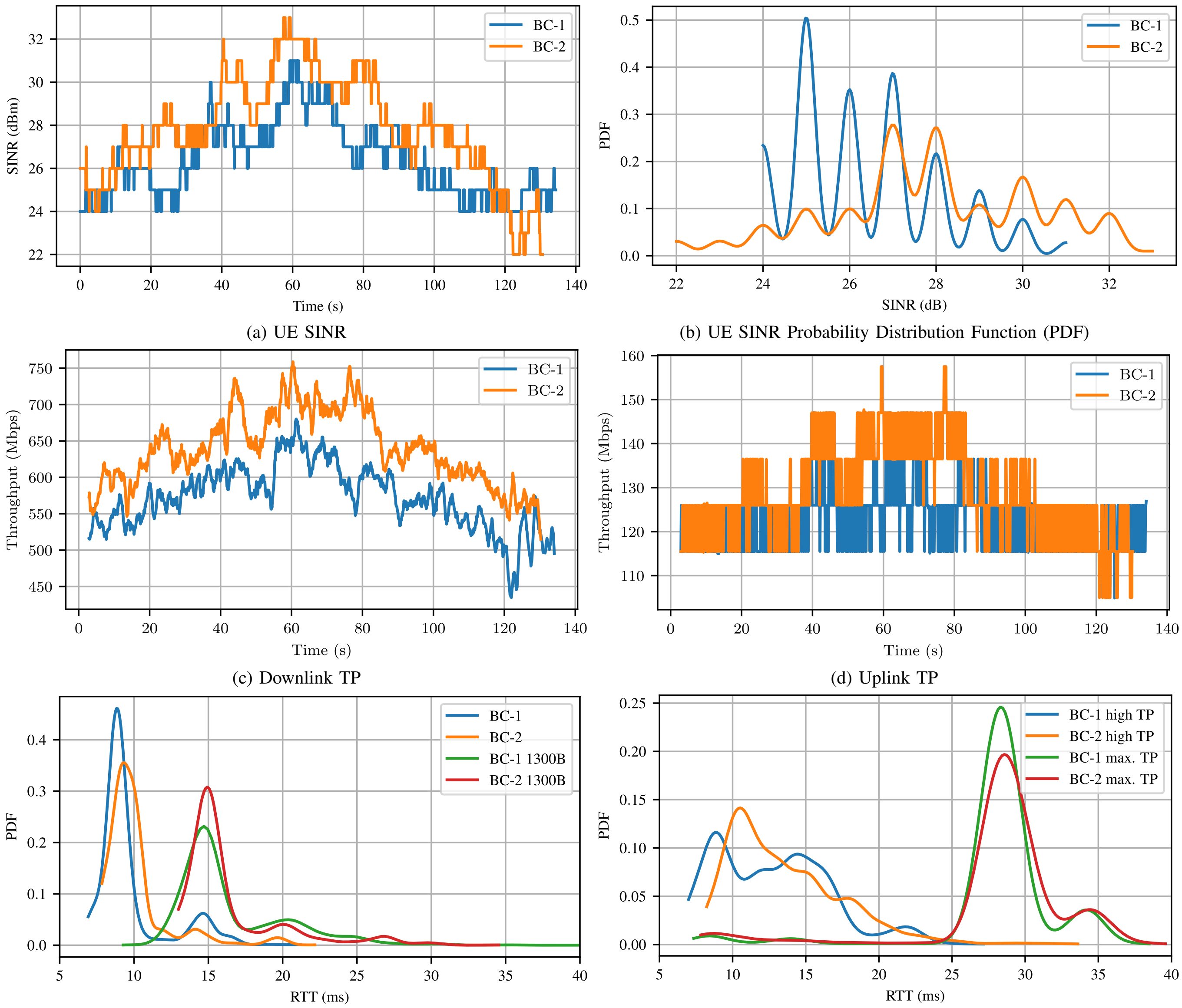
TABLE II: Parameters for acquiring situational awareness

Parameter	Source	Type	Remark
Communication endpoints	OT DT	Dynamic	IP addresses
AoI	OT DT	Dynamic	Coordinates
Movement speed	OT DT	Dynamic	Per AoI
TP requirement	OT DT	Dynamic	Per AoI
Delay upper bound	OT DT	Dynamic	Per AoI
Packet sending rate	OT DT	Dynamic	Per AoI
Packet loss tolerance	OT DT	Dynamic	Per AoI
Number of cells	RAN[1]	Static	
Bandwidth	RAN	Static	Per cell
TDD pattern	RAN	Static	Per cell
Position of TRPs	RAN	Static	Per cell
Numerology	RAN	Static	Per cell
MIMO[4]support	RAN	Static	Per cell
5QI[5]	UDM[2]	Static	Per UE
Subscriber data	UDM	Static	Per UE
Position	LMF[3]	Dynamic	Per UE
CQI[6]	RAN	Dynamic	Per UE, measured
Data rate	RAN	Dynamic	Per UE, measured
UL/DL latency	RAN	Dynamic	Per UE, measured
PDV	RAN	Dynamic	Per UE, measured
Resource utilization	RAN	Dynamic	Per cell, measured
No. of serving UEs	RAN	Dynamic	Per cell, measured

[1] Radio Access Network (RAN)
[2] Unified Data Management (UDM)
[3] Location Management Function (LMF)
[4] Multiple-input/multiple-out (MIMO)
[5] 5G QoS Identifier (5QI)
[6] Channel Quality Indicator (CQI)

is equipped with a stand-alone 5G system and serves as a genuine 5G testbed area beside the production. The 5G testbed uses n78 frequency band and Time Division Duplex (TDD) scheme 8:2 (8 Downlink (DL) slots and 2 Uplink (UL) slots in a frame). An AMR has been used to scan the area with the LiDAR sensor and also for automated network performance measurements. The factory covers an area of $1600\,\mathrm{m}^2(40{\cdot}40\,\mathrm{m})$. The figure shows only part of the factory floor that is of the highest interest for our use case, as it has two distinct paths between the marked points B and C. The gNB TRP is located behind the wooden wall that separates the factory into multiple parts. Thus, the SINR values are highest in this area, as shown in the overlaid SINR heatmap. The heatmap also shows a significant reduction of radio coverage when moving to the remaining parts of the factory.

A use case has been designed to demonstrate the benefits of the aforementioned interaction between the network and OT domains. The AMR has the task of carrying an object from point A to point C, as marked in Fig. 5. There are two possible paths toward the end goal and at point B, the OT system can choose which path to take. Without insights into the 5G-related parameters, such as SINR and resource utilization, the OT fleet controller would choose the shortest possible path BC-1. However, from the radio network perspective, these two paths are not the same and a different number of UEs can be served at each one. In this case, the 6G DT could generate a capacity map that provides the number of supported UEs on each path. The OT domain does not need to be aware of network domain radio parameters and implement the logic to interpret them. Therefore, the number of supported UEs, which depends on UE communication requirements and network conditions, is chosen as a common Key Performance Indicator (KPI) that both domains understand. As can be seen on the SINR heatmap, part of the BC-1 path has a lower SINR



(a) UE SINR (b) UE SINR Probability Distribution Function (PDF)

(c) Downlink TP (d) Uplink TP

(e) Round Trip Time (RTT) PDF with different packet size (f) RTT PDF with background traffic

Fig. 6: SINR, TP and RTT measurements on two routes

compared to the BC-2 path. This results in higher resource utilization on the BC-1 route for the same traffic requirements. Fig. 6 shows the SINR, TP in DL and UL direction and RTT measurements performed by the AMR UE on both routes. The measurements show only results from AMR round trip on the routes BC-1 and BC-2 as this is the area of interest. The route BC-2 has higher average SINR (Fig. 6a and Fig. 6b), which results in 10 percent more TP in DL and UL direction on this route than on the route BC-1, as seen in Fig. 6c and Fig. 6d. The TP measurements are made using the Iperf3 tool. A realistic assumption can be made that 500 Mbps of DL data is generated by the stationary UEs and that needed resources are pre-reserved. If cooperative AGVs require 5 Mbps of TP in UL and DL for the cooperation as given in [17], the BC-2 route can support 2-3 cooperative robots (4-6 UEs) more in average compared to BC-1 route as the difference in UL TP is 10-20 Mbps. The difference in TP is more noticable in DL channel as the TRP transmitt power is fixed, while in the UL channel, the UE can adjust the transmit power up to certan level and mitigate the SINR drops. Additional latency measurements were made using the Isochronous Round-Trip Tester (IRTT) tool. We focused on RTT measurements as the 5G testbed does not yet support wireless time synchronization and UE mobility is required. Fig. 6e shows the RTT PDF without additional network traffic but with packet sizes of 64 B and 1300 B. There were no significant differences in RTT values between the routes. A similar result is obtained in the second test case, where a different UE was generating background traffic while the RTT packet sizes were set to the default value. One test was made with high background traffic of 100 Mbps and 600 Mbps in UL and DL direction, respectively and one with maximum traffic in both directions. Although Fig. 6f shows an increase of mean value as well as increased variance of RTT compared to the first test case, the difference between the two routes is not significant. The reason is the configuration of the 5G testbed. The 5G testbed does not support high reliability and low latency 5QI and therefore, the IRTT traffic is sent with best-effort QoS, meaning, the required TP, which is low for IRTT measurements, is prioritized instead of low latency. However, certain differences in latency exist on two routes and based on differences of SINR PDF distribution on Fig. 6b, a possibility exists that the one route with higher average SINR is more suitable for higher TP requirements while the other route with lower SINR variance is better for lower latency requirements. The differences between multiple possible routes between two goals can be more significant than in this case and therefore, the benefits of joint task planning are more excessive.

V. Conclusion

Digital Twins (DTs) are valuable assets in industrial Cyber-Physical Systems (CPSs) with widespread usage today, for instance, regarding optimization and maintenance of CPSs. As DTs continue to proliferate, for instance, with increasing adoption to networking, it is likely that a collaborative utilization of DTs will emerge that spans beyond each application domain of DTs. This paper describes possible usage and benefits from the interaction between the DT of a 6G Network and the DT of an industrial OT system (like a manufacturing system), leading to the concept of Situational Awareness (SA) to provide better support for critical applications in the industrial CPS. A realistic use case from manufacturing is considered, where we identify several critical operating points that would facilitate cross-domain interactions via DTs. Based on this concept, we present several examples of SA arising from the interactions between the network and the OT. These examples illustrate how joint task planning and execution becomes possible by exchanging such SA between the domains via their respective DTs. The potential benefits of joint task planning are also demonstrated through measurements in an industrial 5G testbed. We believe that many more such use cases exist, and we see the future consideration of the interactions between DTs of the two respective domains as an important future direction.

VI. Acknowledgements

This work was supported by the European Union's Horizon Europe project DETERMINISTIC6G under grant agreement No. 101096504.

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