DOI: 10.2195/lj_proc_priyanta_en_202310
URN: urn:nbn:de:0009-14-58126

Towards 6G-Driven Digital Continuum in Logistics

Auf dem Weg zu einem 6G-gestützten digitalen Kontinuum in der Logistik

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The digital revolution has transformed the logistics industry into a dynamic, data-centric environment. The proliferation of the 5G network towards 6G is expected to shape the future of the logistics field by unleashing disruptive technological innovations. 6G has enormous potential, paving the way for the "Digital Continuum," a new paradigm in logistics. This concept features advanced Digital Twins working together as a unified and adaptable data-driven framework. In this work, we use Logistics Living Labs to investigate how to apply 6G technology to a Digital Continuum space. Therefore, we present an overview of 6G-driven novel applications in the intralogistics domain including their benefits, challenges, and insights into their technical setups.

[Keywords: 5G, 6G Technology, Digital Twin, Intralogistics, Autonomous Mobile Robots]

Die Logistikbranche hat durch die digitale Revolution einen Wandel zu einer dynamischen, datenzentrierten Umgebung erfahren. Es wird erwartet, dass die Weiterentwicklung von 5G zu 6G die Zukunft der Logistikbranche prägen wird, indem sie bahnbrechende technologische Innovationen ermöglicht. 6G bietet ein enormes Potenzial und ebnet den Weg für das "Digitale Kontinuum", ein neues Paradigma in der Logistik. Dieses Konzept zeichnet sich durch fortschrittliche digitale Zwillinge aus, die in einem einheitlichen und anpassungsfähigen datengesteuerten System zusammenarbeiten. Im Rahmen dieser Arbeit wird mithilfe eines logistischen Reallabors untersucht, wie die 6G-Technologie in einem digitalen Kontinuum eingesetzt werden kann. Hierfür geben wir einen Überblick über neuartige 6G-basierte Anwendungen in der Intralogistik, ihre Vorteile sowie Herausforderungen und einen Einblick in ihre technischen Setups.

[Schlüsselwörter: 5G, 6G Technologie, Digitaler Zwilling, Intralogistik, autonome mobile Roboter]

1 Introduction

An efficient and optimized logistics supply chain is the cornerstone of industries' business operations. Logistics operations are intricate, involving numerous partners distributed worldwide. Many businesses confront increasing difficulty meeting consumer expectations for customization as global market demands are evolving [1]. Uninterrupted material flow in intralogistics is one of the keys for working supply chain systems. To achieve the goals, large numbers of data must be processed thoroughly. Thanks to the technological developments in the Industry 4.0 era, logistics business processes shifted to intelligent data-driven decision-making and incorporated cyber-physical systems (CPS) [2].

The challenge of developing algorithms for predictive behaviors is addressed by simulation-based Artificial Intelligence (AI), which uses big data and environment settings to simulate logistical processes [3]. These simulations are transformed into a CPS-based framework called Digital Twin (DT), enabling the concurrent design and execution of operations in both virtual and physical worlds [4]. Furthermore, 5th Generation (5G) and future 6th Generation (6G) mobile communication networks enable ultra-low latency connectivity and close the gap between digital simulation (virtual) and simulated reality (physical) systems. This means that the components in both worlds are intertwined and fully synchronized in a continuum space of a logistics system. Behavioral models can be generated autonomously over time. In this way, logistics systems evolve into being highly responsive and automatically adaptive to the demands of the environment. As a result, the "Digital Continuum" paradigm emerges as the evolution of this new brand of DT and is expected to revolutionize logistics business processes.

6G technologies explore new spectrum bands of mmWave and µmWave (Terahertz) and offer massive-ULC (Ultra Reliable Low Latency Communication) with 100 times higher connectivity, whereas 5G poses limited data rates and overhead network traffic [5], [6]. These KPIs

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enable a reliable network with real-time capability and ultra-high data rates for massive communications across platforms. 6G technology focuses on integrating multiple radio access technologies (RAT), which leads to questions:

- How to emulate and validate the 6G-driven experiments?
- How does the system interoperability of 6G technology work in existing logistics networks and automation systems?

To answer the questions, we introduce the Digital Continuum in logistics in the form of an intralogistics scenario. We propose the usage of a Living Lab (*Reallabor*) to emulate the intralogistics technical setups and produce the validation results. This journal provides an overview of four 6G-driven novel applications in intralogistics: i) Radio Frequency (RF) based localization using grid-based Sensor Floor network, ii) Data-driven 3D Radio Environment Mapping (REM), iii) Digital Network Twin (DNT), iv) 3D Network Management. Additionally, we present the benefits as well as challenges and insights into technical setups for the intralogistics domain.

2 FUNDAMENTALS

2.1 LOGISTIC 4.0 AND CYBER PHYSICAL SYSTEM

The fourth industrial revolution, or "Industry 4.0," describes the increasing digitalization and networking of production processes, machines, and industrial plants. This includes using CPSs, the Internet of Things (IoT), AI, and other technological developments to create intelligent and networked production environments[7]. Logistics 4.0 has emerged in recent years. The advancement of information and communication technologies (ICT) made it possible to introduce new techniques of sharing data, connect different stages of production and distribution, and innovate new ways of conducting business [8]. Logistics 4.0 is relevant for the future of the warehouse, due to its high share of employment in the logistics industry. It involves supporting and shaping digitalization as well as automation of cross-company as well as cross-functional coordination tasks in logistics [9].

Logistics 4.0 refers to the networking and integration of logistics processes within and outside of companies, with real-time control based on CPS [10]. CPS consists of networked, information technology and software components embedded in mechanical and electronic parts, which can communicate and coordinate independently via the internet. The focus of CPS is on networking and the shared use of existing data and processes [11]. By using CPS, plants, machines, and individual workpieces as well as production and logistics processes can share information and process it instantly, enabling real-time control and coordination across distances and companies.

2.2 5G/6G MOBILE COMMUNICATION NETWORK

The fifth generation (5G) of mobile networks has revolutionized wireless communication by enabling high data rates, reliability, scalability, and low-latency communication. 5G has features that cater to specific requirements but can also be used in other contexts. These features include extreme mobile broadband (xMBB), massive machine-type communication (mMTC), and ultra-reliable machine-type communication (uMTC). The xMBB refers to the ability of 5G networks to deliver extremely high data transfer rates, as well as to reduce delay times during increased network utilization and thus provide a stable network [12]. The mMTC enables numerous interconnected devices, especially valuable for IoT and the automation of production environments [12]. The uMTC supports low-latency connections with high connection for applications such as networked manufacturing or automated driving [12].

Addressing the trilemma of conflicting properties is achieved through network slicing, where the physical network is divided into digital slices configured via software to fulfill defined needs [13]. Other technologies that enable higher data rates and capacities of networks in 5G are massive MIMO (Multiple-Input Multiple-Output) and beamforming [12], [14], [15]. With massive MIMO, multiple antennas are installed to transmit signals simultaneously. The dimension of low latency can be addressed by edge computing. Edge computing is a concept where data processing and storage takes place closer to the source of the data instead of processing it in remote data centers and is thus in contrast to cloud computing [15].

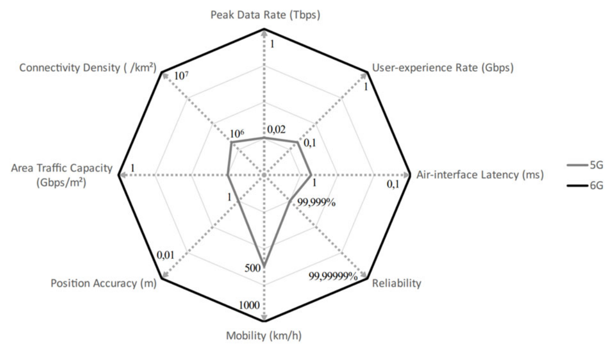

Figure 1. KPI's comparison of 6G and 5G technology, adapted from [16]–[18]

As the commercialization of the fifth generation of mobile communication networks continues to grow, there is already notable curiosity about technologies extending beyond the realm of 5G [16]. In this regard, research is already being conducted on the subsequent communication technology called "6G". 6G technology is expected to offer a huge improvement in network performance, connectivity and applications compared to its predecessors. The development of 6G is still ongoing, but experts predict that the technology will be commercially available by 2030 [17].

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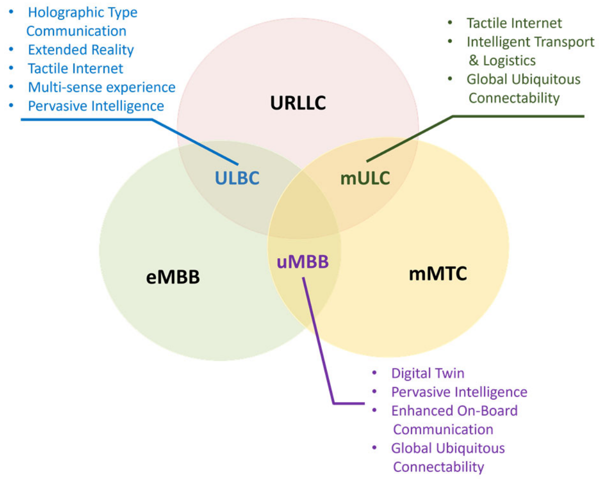


Figure 2. The extension of 5G features in 6G system [17]

6G technology promises to further revolutionize the digitalized and connected world, especially in logistics, which can benefit enormously from faster and more efficient processes. 6G technology extends the 5G main features of xMMB, mMTC, and uMTC to the next level which are respectively [17]: ubiquitous mobile broad-band (uMBB), ultra-reliable low-latency broadband communication (ULBC), and massive ultra-reliable low-latency communication (mULC). Their applications are depicted in Figure 2. To distinctly emphasize the distinct characteristics and outline the technological prerequisites of 6G, we provide envisioned potential use cases:

Terahertz communication: 6G technology will enable frequencies in the terahertz range (0.1 - 10 THz), leading to extremely high data rates of up to 1 Tbit/s [17]. In addition, higher bandwidths can be achieved through these high frequencies, which then enable a connection density of 10 million devices/km^2 (10 devices/m^2) [17].

Low latency: 6G technology is expected to enable latency of 10 to 100 µs, which is equivalent to 0.1 ms, a tenfold improvement over the latency of 5G technology [19].

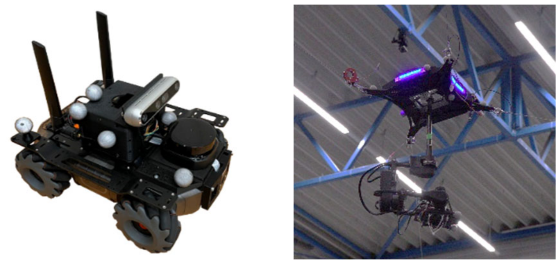
Integrated Sensing and Communication (ISAC): Due to the nature of the high frequency of 6G, the beamforming signal offers a sensing feature allowing to detect the objects (non-networking devices) like radar [20]. Besides sensing, the 6G signal is envisioned to transmit wireless connectivity simultaneously [21].

Reconfigurable Intelligent Surface (RIS): The higher frequency bands of 6G cannot penetrate objects in case of non-line of sight (NLOS) paths. To tackle the issue, RIS evolves an uncontrollable wireless environment into the controllable one by reflecting the beamforming signals of 6G [19].

The 6G technology is expected to be a game changer, as it combines digital technologies with the physical world to create intelligent systems that reshape people's lives. Furthermore, the evolution of the 6G network builds on technologies from 5G, such as digital twins, artificial intelligence, and other concepts. By utilizing these concepts, 6G developers can simulate the physical world more closely, allowing for a deeper analysis and the ability to bring practical measures into the physical world [22].

2.3 Autonomous Robotics Platforms

In this sub section, we describe the autonomous mobile robot (AMR) platforms as the key enablers for the 6G experiment testbed.



(a) (b)

Figure 3. (a) Omnidirectional robot platform (b) Cable robot platform

2.3.1 Omnidirectional Robot Platform

Figure 1(a) shows an omnidirectional robot, offering the advantage of moving in confined spaces and following complex trajectories. Omnidirectional mobility is beneficial for intralogistics environments, as more space is available for shelves. The robot is further equipped with communication technologies, such as Wi-Fi 6, COTS mesh technology, and 5G connectivity.

2.3.2 Cable Robot Platform

The testing environment offers a three-dimensional aerial cable robot, as shown in Figure 1(b), which covers the whole testing area of 21x11m and can dynamically follow trajectories. Cable robots are an enabler for novel three-dimensional networking architectures that can be installed in industrial halls, as they can hold mobile base stations and provide wired fiber cables as a backbone connection. Besides their practical use case, the cable robot allows mimicking UAV mobility in the scaled environment without safety concerns.

3 Related Works

The Digital Continuum's data-driven paradigm has received much attention lately, mainly focusing on the logistics industry and the transition from 5G to the future 6G mobile networks. A framework of interconnected systems and innovative applications is being created in this domain.

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In this section, we conduct comprehensive literature on these emerging technologies in logistics.

3.1 Digital Continuum

"Digital Continuum" term was used by Wallen [23] to point out the implication of a continuous digital environment where the digital content can be transformed, created, reproduced, and transmitted virtually. Micken, et al. [24] reshaped the Wallen concept [23] and proposed a "Digital Continuum" framework emphasizing the concept of digital offerings that define the conceptual model of digital products and digital services in general. The authors [24] suggest various dimensions of Digital Continuum such as control, customization, and ownership-access in digital domains. The vision of the Digital Continuum has become a transformational force in logistics by involving a scalable data-driven approach [3]. By bridging the Digital Continuum concepts [23], [24] of the "data-first" paradigm to the logistics context, the resulting aspects can be considered in the followings:

Ownership, Access, and Control of Logistics Data [24]**,** [25]**,** [26]**,** [27]**:** The concept of ownership and access, and control is related to how logistics companies handle data from various sources, such as IoT devices, robots, warehouse inventory systems. When the data is owned and managed properly, it can be integrated into digital twin systems and dataspaces, allowing diverse stakeholders to collaborate and enhance supply chain optimization.

Cocreation and Collaboration of Dataspaces in Logistics [24], [26], [28]**:** The cocreation and collaboration concepts are in line with the collaborative nature of data-driven digital twins in logistics, where different stakeholders provide information for thoughtful decision-making. This approach increases flexibility and efficiency by modifying inventory levels and optimizing delivery routes based on real-time data. Cocreation is also strongly related to dataspaces in the IoT-edge cloud continuum, which facilitates integrated data environments in logistics. These collaborative dataspaces enable participants to co-create solutions, improving the accuracy and depiction of real-world logistical dynamics in digital twin models.

Digital Offerings and Enhanced Logistics Services [24], [27], [29], [30]**:** By analyzing how technology-driven solutions improve logistics services, the idea of digital offers may be expanded to the logistics industry. For instance, real-time tracking and visibility tools, demand forecasting using predictive analytics, or route optimization using AI are all examples of digital products. The consumer experience, operational effectiveness, and logistics decision-making are all impacted by these digital services. The value that these digital services bring to various stakeholders within the logistics ecosystem may be influenced by the degree of access and control over them.

Logistics Applications and Symbiotic Evolution [1], [3], [24], [27], [29]**:** Both the Digital Continuum and the IoT-edge cloud continuum emphasize the evolution of digital offerings. In logistics contexts, the symbiotic evolution between digital twin systems and dataspaces aligns with the continuous enhancement and adaptation of supply chain and warehousing operations. Integrating IoT data at the edge and cloud-based analytics allows for constantly refining digital twin models, enabling logistics companies to make data-driven decisions that reflect real-time conditions and changing demands. Herein lies the concept of a cyber-physical twin. It automatically gains behavior knowledge through simulation experiments and applies it to real-world situations.

3.2 5G/6G Technology Applications in Intralogistics

To achieve the goal of 6G standardization in 2030, researchers worldwide have started 5G/6G projects in various test fields. Logistics, especially intralogistics, is envisioned to be one of the critical industry sectors for 5G/6G applications. Therefore, this subsection presents a brief overview of existing 5G/6G surveys of intelligent warehousing systems.

GAIA-X [28] aims to develop federated data infrastructure among European businesses and governments. In this project, 5G connectivity enables deterministic networking for trusted networked production and logistics based on cloud services. The federated trustworthy AI in the cloud is the core of GAIA-X architecture, especially in predictive maintenance, match-making demand, and supply chain actors. Providing real-time remote cloud-based and edge-AI services are the current challenges for "cloudification."

A recent review of Automated Guided Vehicle (AGV) [31]–[33] explores the optimization of AGV fleet management in warehousing by researching how are the potentials of 5G radio technology in millimeter wave (mmWave) region and Mobile Edge Computing (MEC). Utilizing 5G and MEC, AGVs can be controlled, centralized, or decentralized. This integration enables AGVs to access global navigation information, improve system optimization, and support efficient navigation within factories using reliable 5G massive MIMO antenna networks. However, the risk of a single point of failure with a MEC necessitates backup solutions. Research into hand-off strategies during MEC failures, mitigating signal penetration losses, and robust control systems on the 5G MEC platform are crucial to ensure reliable fleet management.

6G use cases in logistics have been reviewed in the works of [5], [16], [17], [34], [35]. The authors primarily concern the KPIs and technical requirements to implement emerging applications. The specific implementations and experiment testbeds should be discussed in these works. In addition, **a comprehensive view of the initiatives on the**

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6G research is delivered by the researchers in [35] [36]. The research projects mainly contribute to the rough roadmap for technical specifications, standardizations, and novel use cases. Only a few projects consider the technical setups for logistics context as their focus.

REINDEER project [35], [36] builds novel Radio Weaves technology, which is novel beyond 5G infrastructure. The goal is to create intelligent, interconnected computing platforms employed as a distributed antenna array. This infrastructure is aimed at the logistics domain to perform high-accuracy localization and enhance the broadband connectivity between robots or humans to robots. The current experiments are validated in an open 6G testbed, a laboratory-based setup called Techtile [37].

DEDICAT6 project [35], [38] aims to advance from B5G to an intelligent 6G platform. In the context of smart warehousing, the aim is to apply concepts such as distributed intelligence and computation offloading to optimize warehousing operations, and to enhance employee training and maintenance through augmented reality. The project also seeks to facilitate human-robot interaction, improve safety, enable remote inspection and diagnostics, and enhance the identification and tracking of goods throughout value chains. DEDICAT 6G system architecture involves the dynamic distribution of intelligence between devices (i.e., Locobo WX250 robot platform), edge, and cloud using flask, while considering the heterogeneity of technologies used. It also includes mechanisms for dynamic coverage and connectivity extension through the utilization of diverse devices such as drones, robots, connected cars, and other mobile assets in a warehouse.

These publications frequently offer general explanations without delving further into technical setups or specific testbeds. Therefore, a more comprehensive and applied research approach is required that focuses on the intralogistics domain.

4 Methodology

To investigate the potentials and challenges of 6G-driven applications in the intralogistics domain, we introduce the concept of a Living Laboratory as a controlled experimental testbed. The idea of a "Living Lab" for logistics is described as a dynamic field that simulates a data-driven environment, enabling the testing of novel technologies in practical settings and producing artificial data from virtual models [3]. This Living Lab enables the systematic application of empirical and experimental methodologies across multidisciplinary fields by continually integrating high-quality data from actual logistical scenarios into a simulation environment [3]. Hence, the technical overview can be drawn, e.g., validation results and the gap between virtual/physical experiments. Figure 4 illustrates how the Innovationlab TU Dortmund University [39] and PACE lab Fraunhofer IML [40] bridge the real-world and virtual systems, which function as our Living Labs in this work.

The Living Labs provide a 6G validation environment for performing reproducible and cost-effective tests with unique features, such as ground and aerial vehicles with different scaling options and high dynamics. Either real-world scales (1:1) or higher scales are possible by adjusting the mobile communication parameters to emulate bigger ranges and harsher environments. Reflective obstacles and attenuation pads can be introduced to emulate shadowing effects and reduced signal strengths. The intralogistics scenario is the main focus of the Digital Continuum in logistics. The 3D-automated intralogistics environment is the physical system of our intralogistics scenario in Figure 5 and is located in the Living Lab.

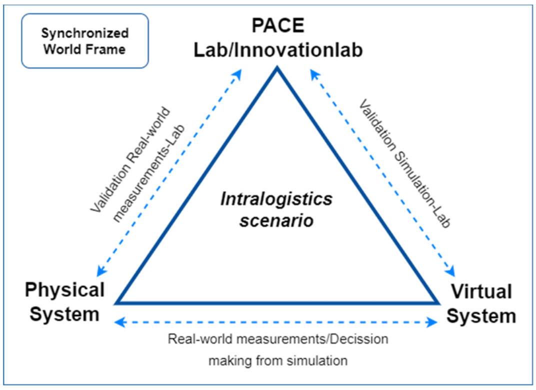

Figure 4. The usage of Living Lab approach to perform the particular test scenarios and link the gap between physical and virtual systems, adapted from [3].

This scenario involves different entities like wireless sensor networks (WSN), humans, and autonomous robots. In the scenario, omnidirectional robots are envisaged to utilize 5G or future 6G radio technology to perform the warehousing tasks, such as orchestrated movements of picking up and transporting parcels. The swarm robots can get their current positions from the RF-based localization using 5G/6G ISAC or “Sensor Floor”. Additionally, communication takes place in the form of massive D2D (device-to-device) between the robots and WSN, as well as to diverse RAT.

A 3D-aerial cable robot system, geared with an antenna or router, is mounted to the ceiling of the hall for measuring and validating the radio propagation channel of the warehouse. Furthermore, reflector walls improve the network coverage and simulate different warehouse setups, as the 6G signals cannot penetrate objects. [19]. These passive and active reflector walls are used for simulating different locations, like warehouses, and different setups of these warehouses. A motion capture (MoCap) system with sub-mm localization accuracy is used as a reference system.

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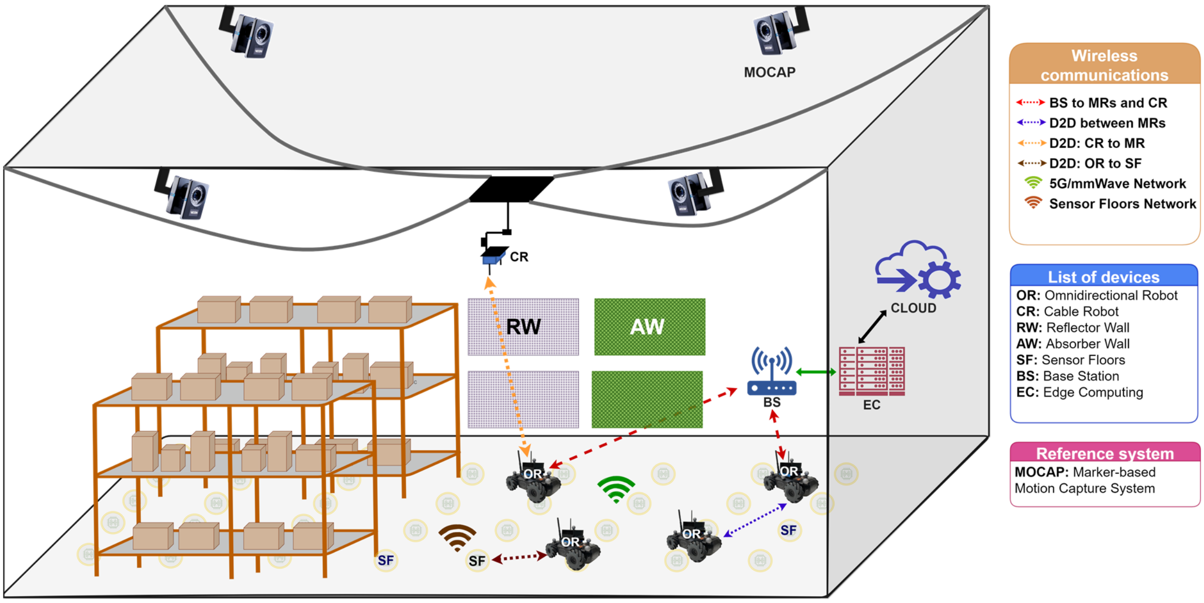

Figure 5. Illustration of intralogistics scenario and setup

5 Technical Overviews of Intralogistics Scenarios

6G technology focuses on integrating multiple RAT, which means the existing wireless technologies such as WiFi, 4G, and 5G. This section provides technical overviews of future 6G-driven RF applications for the Digital Continuum in logistics. The overviews highlight the technical setups, interoperability with existing infrastructure as well as their potential and challenges. The presented overviews are the work-in-progress research that is related with application of the Digital Continuum concept in logistics.

5.1 RF-Based Localization using Sensor Floor

Several applications of the Sensor Floor have been implemented for intralogistics, including radio flooding protocols [41] and RF-based robot localization [42]. RF-based localization is a feasible approach in the case of vicinity of camera-based system in logistics system. The robot localization introduces a machine-learning-based method that utilizes the measurements of the Received Signal Strength Indicator (RSSI) and Inertial Measurement Unit (IMU) data of Sensor Floor [41], [42]. This platform has been implemented in Innovationlab as a grid-based WSN platform.

The Sensor Floor serves as a low-power distributed sensing platform arranged as a 30x15m^2 grid with a total of 345 nodes. Each column consists of 15 SensorTag nodes connected through the 1-Wire protocol to a Raspberry PI. These nodes enable various research applications. Each node is equipped with a Texas Instrument CC1350 SensorTag, containing ten low-power MEMS sensors for detecting motion, temperature, humidity, pressure, light, magnetic field, and sound. The CC1350 SensorTag operates on sub-1 GHz frequency bands and 2.4 GHz of Bluetooth low energy (BLE). A Message Queuing Telemetry Transport (MQTT) protocol transmits the nodes' measurement data to an MQTT server through an internet-connected Raspberry Pi. A toolkit was designed and created for the Sensor Floor to perform data gathering and flashing easier.

A Convolutional Neural Network (CNN) was developed to predict the 2D location of the robot. The RSSI and IMU data are treated as a heatmap of a 23x15 array as the input for the CNN layer. The ground truth is the 2D coordinates of the robot from the MoCap system. The CNN exhibits remarkable accuracy, being able to track and monitor the robot's movement with a precision of ≈15 cm [42]. It emphasizes how well CNN reduces radio signal noise and multipath interference. Even if the approach must train and collect data again for every new arrangement, adding a self-calibration mechanism might make it

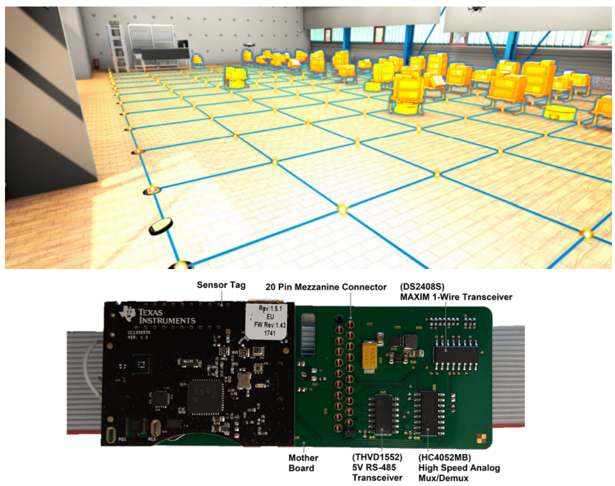

Figure 6. Rendered picture of the placement of Sensor Floor nodes and the implementation of a node using CC1350 SensorTag and extension board.

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more useful. The approach performs consistently because the training data and inference are consistent within the same environment. The experiment setup, hardware, and software are open source under https://github.com/FLW-TUDO/sensorfloor.

This project considers two approaches to extending the existing physical Sensor Floor network. In the first approach, some existing parts are replaced with new 6G-capable sensors. The second approach integrates future 6G network infrastructure with the existing Sensor Floor network. Hence, the heterogeneous types of wireless communication are managed via a Multi-X-Broker (xApps) [43]. This allows for optimal resource allocation of various wireless standards, such as using the Sensor Floor platform for 6G-based localization or fully utilizing 6G ISAC-based [21]. Additionally, 6G research goals, such as efficient and intelligent 6G network slicing management, can be explored through this approach.

5.2 Digital Network Twin

In recent years, DT applications have expanded to the communication field due to the proliferation of 5G and 6G mobile networks. 6G technology is envisioned as self-sustained wireless systems [44]. This new concept emerges in general DT into Digital Network Twin (DNT), which transforms the classical network modeling to the data-driven virtual network twin model of the physical network in real-time [44]–[46]. The significant key role of DNT is its intelligent analysis using AI. DNT, in combination with AI, has demonstrated novel functionalities like real-time network optimizer, network planning, and simulating what-if analysis [45], [46]. In this manner, the DNT acts as a self-organized network and can realize the 6G goal of a self-sustained network.

The intralogistics environment is constantly evolving and involves a collaborative effort between humans and robots to pick and transport parcels from various stations and shelves. These dynamic changes in warehouse layout impact the network configuration over time. DNT enables the network systems of the warehouse to act and adapt intelligently based on the current scenario using real-time data from WSN, robots, or warehouse operators. Figure 7 shows current DNT prototype, which consists of three domains:

Physical domain: DNT accommodates various intralogistics scenarios in the physical domain, as explained in section 4 and illustrated in Figure 5. The physical infrastructure is integrated with the reference system and 6G-driven applications in this domain. 3D REM and 3D network management are the applications of cable robots, which are explained in the following subsections. A laser projection system offers the visualization of each scenario through immersive augmented reality (AR).

Digital twin: The twin core is the application programming interface (API) bridge to associate real-world scenarios and the physical network with the visualization layer and virtual domain. The visual metaphor layer is implemented in the form of a 3D GUI that is coupled with a laser projection system based on AR. Instead of network visualization in the virtual world, we visualize the network twin to the physical world. Hence, simulated environments, i.e., virtual objects, robots, and network infrastructures, are projected and emulated in the real world.

Virtual domain: Two functions in this domain focus on virtual mobility and the virtual network. Most DTN structures [44]–[46] are computationally intensive due to data-driven and intelligent network modeling and optimization. Consequently, the virtual domain is suggested to operate on an edge- or cloud-based computing platform [44]. Virtual mobility simulates the swarm robots' scenario of coordinated movements. A virtual network is the heart of DNT to model the physical network in the virtual world and optimize the network configuration intelligently. To perform these tasks, the classical network simulation, i.e., ns-3 and OMNET++. Additionally, data-driven-based network simulations (DDNS) have been introduced in [47], [48] that signify the Machine Learning model to optimize the communication system for vehicular system.

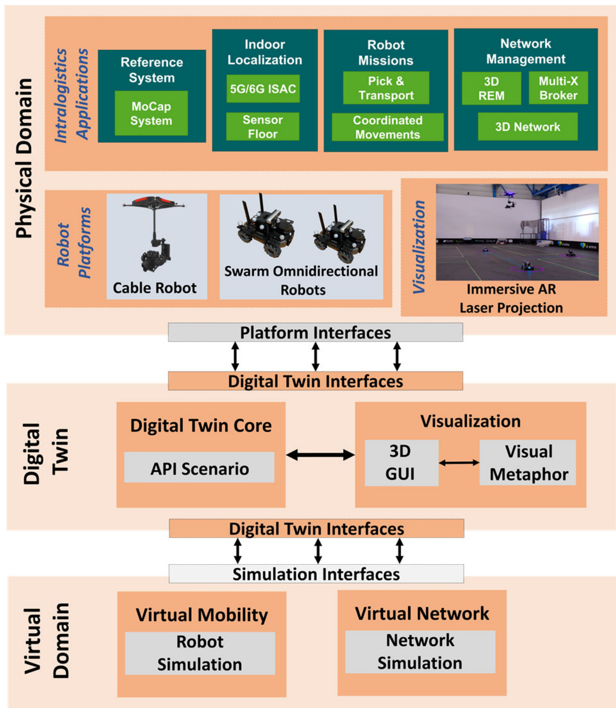

Figure 7. The proposed digital network twin architecture

The DNT is work-in-progress research offering plug-and-play functions of different physical scenarios and virtual systems using MQTT protocol or API plugin. As the first proof of concept, 3D REM and 3D network management approaches are presented in subsections 5.3 and 5.4, respectively, as the application of the current DNT prototype.

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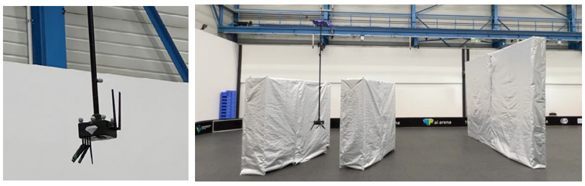
5.3 DATA-DRIVEN 3D RADIO ENVIRONMENT MAPPING

An important component of future warehouses is the fully automated network planning for 5G or future 6G networks. Due to constant environmental changes within the intralogistics, such as frequently changing storage situations and dynamic obstacles, non-stationary ad-hoc networks are essential for reliable network solutions.

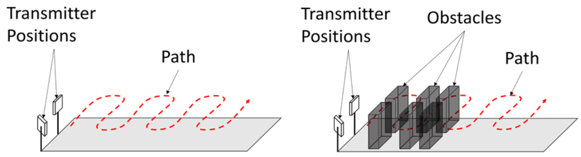


(a) (b)

Figure 8. The technical setup for 3D REM: (a). 5G receiver on cable robot as data collector. (b). Measurement setup scenario using heavy-duty shelves.

The 3D RF mapping research application introduces a novel method for predicting signals strengths in ad-hoc network planning. This approach employs a 3D-aerial cable robot system, Software Defined Radio (SDR) technology, and Machine Learning techniques. This setup enables the system to forecast the Received Signal Strength (RSS) at the receiver's location based on the transmitter's position within an intralogistics setting. As a database for this application, different intralogistics scenarios have been investigated. Instead of placing high-bay shelves within the research area, different layouts of smaller, metallic heavy-duty shelves as well as foldable displays have been utilized. These shelves, covered with reflective materials, simulate intralogistics environments that typically consist of metallic high-bay shelves containing objects that interfere with the radio signals. Apart from one empty hall scenario, further non-empty hall scenarios have been set up, like the one in Figure 8(b). Two folding displays have been placed in front of the transmitter position, followed by four heavy-duty shelves. Further, each scenario has been captured with two different transmitter positions. The path followed by the 3D-aerial cable robot for mapping the environment is illustrated in Figure 9.

The physical data has been complemented by synthetic data for extending the database and therefore enriching the training process of the Machine Learning methods. For this purpose, the DT of the intralogistics environment has been utilized, which includes all necessary material properties of the obstacles and the environment. This research approach accurately represents the wireless communication dynamics in intralogistics environments and generates reliable predictions of RSS values within dynamic settings. Bridging the gap between simulated scenarios and actual logistics operations makes it easier to build and validate optimum network planning strategies for current 5G and upcoming 6G networks in warehouses.



(a) (b)

Figure 9. The illustration for the measurement scenario: (a). reference measurement with empty test field. (b). measurement with obstacles.

5.4 3D NETWORK MANAGEMENT

A further important component of the future warehouse is the 3D Network Management. Situations in which the ad-hoc positioning of base stations is not feasible can lead to black spots in the environment. For instance, high-bay shelves in intralogistics halls result in shadowing effects, such that autonomous robot platforms, which rely on the communication to a base station, cannot operate anymore and in worst case result in accidents.

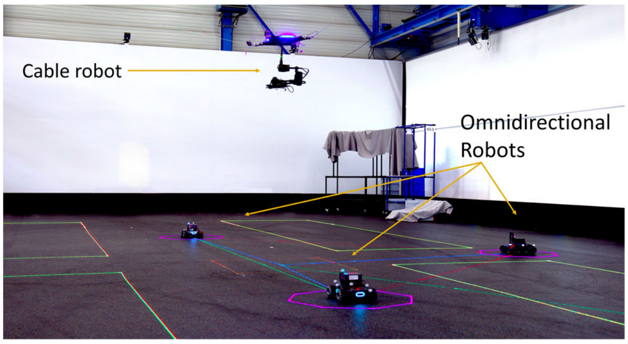


Figure 10. The technical setup for 3D network management in intralogistics, the cable robot is utilized as the relay node to enhance the coverage of omnidirectional robots.

In this research application, an automated intralogistics environment, including real-time DNT impairment of the network behavior, has been fully incorporated into the research hall. It has been utilized for multiple case studies, with variable scaling, allowing the analysis of end-to-end data traffic including mesh routing. Additionally, a visual component has been added to the DT, driven by a laser-based projection system as an immersive AR component. It can visualize trajectories and track boundaries in the scaled research environment. Further, it offers the opportunity to create visual metaphors and illustrate internal network states and can be used for projecting communication links between network entities, as in Figure 11. Intralogistics environments are challenging in terms of radio propagation. The efficient placement of shelves in these environments prevents complete communication coverage. Prior to physically arranging the shelves, tests can be conducted with the robot fleet utilizing virtual obstacles and the DNT, preventing accidents in the event of uncovered regions in the physical testbed. DNTs can also be crucial in the optimization and analysis of network performance.

DOI: 10.2195/lj_proc_priyanta_en_202310
URN: urn:nbn:de:0009-14-58126

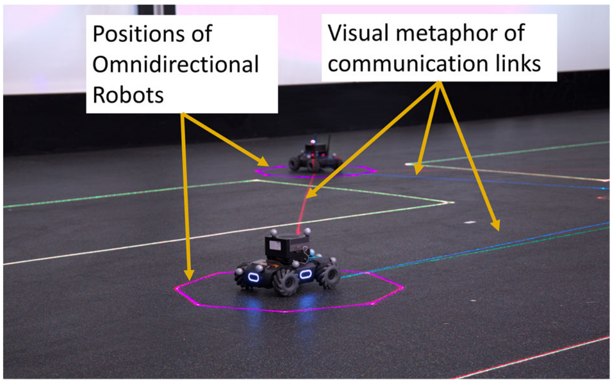


Figure 11. The visualization of connection link between the omnidirectional robots using the DNT.

Within the automated intralogistics environment in Figure 12, virtual and physical transport systems drive to different pick-up stations and transport the packages from there to a common drop-off station. The DNT simulates the intralogistics testbed, consisting of robot platforms, static and dynamic obstacles as well as radio communication, in real-time. Due to high-bay shelves, the transport systems face shadowing effects, and communication is hindered. To overcome the shadowing effects, the idea of 3D Network Management is introduced. Therefore, the 3D-aerial cable robot bridges the gaps in radio communication. It moves to the according black spots and using an intelligent routing algorithm, the connection between the robot fleet and base station can be reestablished.

By bridging the gap in radio communication in 3D space, this research application shows how the concept of 3D Network Management can overcome the challenges resulting from shadowing effects in current 5G and upcoming 6G intralogistics environments. Further, it shows that small-scale vehicles and testbeds are beneficial for developing autonomous platforms as they provide the possibility of testing new algorithms for 3D Networking before transferring them to a 1/1-scale.

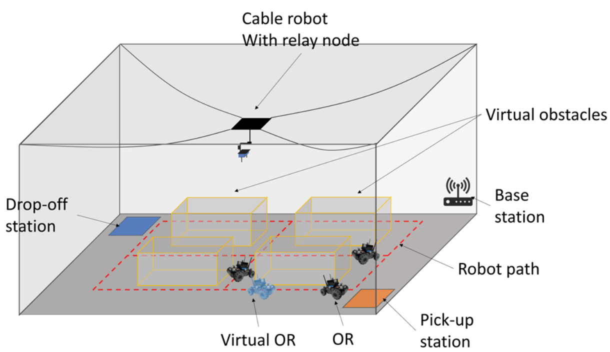


Figure 12. 3D automated intralogistics scenario

6 OUTLOOK

This work presents multiple technical overviews towards 6G-driven Digital Continuum applications. The future 6G ISAC feature and 3D REM are expected to support RF-based localization for tracking multi-warehousing robots in dense and occluded areas. The RF-based localization supports in the case of the vicinity of computer-vision-based localization. However, the 6G-based localization is challenging in the NLOS environment. Therefore, reflector walls like RIS are expected to solve the issue by applying them to the warehouse's wall. DNT closes the gap between real-world and virtual network environments, enhancing the value of research findings for each use-case, i.e., 3D REM and 3D network management. Future DNT research will focus on the implementation of intelligent virtual domains and the 6G-based mmWave network for diverse scenarios.

Further, the heterogeneous type of wireless communication, complex infrastructure, and a 6G network are engaging topics for system interoperability. Consequently, centralized radio access network (RAN) software is suggested to control and integrate all systems in DNT. In the future application, AMR will send massive data streams to edge/cloud computing via a base station. In this manner, intensive operations of computation are performed on the edge. Here, visual SLAM (Simultaneous Localization and Mapping) and 3D REM are processed, and then send the results back to the AMR.

7 SUMMARY

This research contributes to the first proof of concepts for 6G technology towards a Digital Continuum paradigm in intralogistics domain by introducing four novel applications. The concept of a Logistics Living Lab is utilized for each application to emulate a dynamic physical and virtual intralogistics environment in various real-world scale testbeds. The proposed approach lets experts validate 6G-driven novel applications in real-world situations by reproducing simulated data from the virtual world or using physical measurements. The physical network infrastructure offers a better grasp of how communication systems work, making optimizing and validating technologies, protocols, and algorithms simpler. Hence, the technical overviews can be gathered and summarized.

Overall, the technical overviews and outlooks reveal how these novel 6G-driven applications are translated into practical implementations in the intralogistics domain. It lays the groundwork for future deployments of 6G infrastructures, notably in intralogistics, by unveiling viable challenges and solutions. The given novel applications are also expected to benefit the logistics industry. Nevertheless, more research must be carried out to validate the reliability of the industry-grade standard.

DOI: 10.2195/lj_proc_priyanta_en_202310
URN: urn:nbn:de:0009-14-58126

8 Acknowledgement

This project is funded by the German Federal Ministry of Education and Research (BMBF) under the funding announcement ”6G Research Hubs; Platform for Future Communication Technologies and 6G” under the funding code 16KISK038/16KISK041.

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