A Digital Twin Environment for 5G Vehicle-to-Everything: Architecture and Open Issues

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ABSTRACT

The advent of 5G Vehicle-to-Everything (5G-V2X) technology has revolutionized daily life and the economy. However, the complexity of testing 5G-V2X systems in lab and field settings along with the development cost is increasingly challenging. To overcome these issues, the paper proposes the use of Digital Twin technology, which offers a precise, accurate, and controllable lab-based representation of real-world test conditions. The main idea is to design an open-ended digital twin architecture specifically tailored for 5G-V2X, with the aim of fostering innovation in various aspects of autonomous driving. Considering the recent improvement in Open Radio Access Network (O-RAN) and Multi-Access Edge Computing (MEC) technologies in the proposed architecture, it not only facilitates the development and testing of diverse and sophisticated network and communication layers solutions and applications, but also provides a real-time environment to evaluate new artificial intelligence (AI) methods, data and model sharing, and progress measurement in the field of 5G-V2X.

CCS CONCEPTS

• **Networks → Network simulations**; *Network experimentation*; *Network performance analysis*; Network performance modeling; Mobile networks.

KEYWORDS

5G-V2X, Digital Twin, O-RAN, MEC, autonomous driving, artificial intelligence.

ACM Reference Format:
Haitham Y. Adarbah, Mehdi Sookhak, and Mohammed Atiquzzaman. 2023. A Digital Twin Environment for 5G Vehicle-to-Everything: Architecture and Open Issues. In *Proceedings of the Int'l ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN '23), October 30-November 3 2023, Montreal, QC, Canada.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3616394.3618266

1 INTRODUCTION

The pace of the digital revolution is rising at an ever-increasing rate, and as a result, the inclusion of 5G networks into numerous elements of technology has become an essential component of the ever-changing landscape. 5G is quickly becoming a game-changing force in the domain of connectivity [7, 19]. It promises speeds that have never been seen before, decreased latency, and increased capacity, and it is expanding the bounds of what is possible in the digital world we live in. Its disruptive impact can be felt throughout a wide range of industries, from the field of automation to that of healthcare, but the transportation industry is one in which it is particularly audible and influential. The application of 5G technology in this sector will not only have a marginal effect; rather, it will have a fundamental one, one that will change the fundamental ways in which transportation systems function and interact while also paving the way for additional innovation and optimization [3, 6, 18].

Innovative applications such as V2X communication, a key factor in enhancing the dependability, efficacy, and safety of transportation systems, are welcomed in by the new era of increased connectivity. V2X, employing various modalities including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N), promotes safer and more informed driving by facilitating data exchange between vehicles and entities affecting them [21]. The combination of 5G and V2X improves data transmission speeds, reduces latency, and enables real-time communication, which has significant implications for road safety, traffic management, and autonomous driving systems that rely on seamless, instantaneous data exchange [3, 11, 12].

Another forward-thinking idea, known as digital twins, is gaining significant importance in parallel with the ongoing developments in the field of transportation, driven by the integration of 5G and V2X technologies [22, 23]. A digital twin is essentially a virtual replica of a physical entity or system, enabling the creation of an exact digital mirror of the physical object or process. The end result is a dynamic and interactive virtual model that accurately represents its real-world counterpart. This concept allows for rigorous simulations, predictions, and analyses of the mirrored system. As a result, it provides insightful information that can be used to affect decision-making processes. Because of the numerous benefits, this technology has rapidly gained traction across a wide range of business sectors and application areas [13].

The application of digital twin architectures in the context of V2X opens up a wealth of possibilities. These architectures can generate highly detailed simulations of vehicle and traffic systems, creating a complex digital playground for the purposes of testing, analyzing, and optimizing purposes [8]. This virtual environment allows for the accurate replication of every component of the transportation system, including vehicles, routes, and even driving behavior. Consequently, accurate forecasts and efficient scheduling

PE-WASUN '23, October 30-November 3 2023, Montreal, QC, Canada

ACM ISBN 979-8-4007-0370-6/23/10…$15.00
https://doi.org/10.1145/3616394.3618266

of activities become feasible. Moreover, the integration of 5G technology improves the capabilities of these digital twins, enabling real-time updates and low-latency interactions that closely resemble real-world circumstances. Therefore, the convergence of 5G, V2X, and digital twin technologies has the potential to revolutionize the transportation sector, paving the way for the next generation of intelligent transportation systems. This integration promises a future that is more interconnected, efficient, and safe [15].

The convergence of 5G, V2X, and digital twin technologies holds enormous potential however there are significant obstacles. Designing, deploying, and administering these complex structures in real-world situations pose significant obstacles, as our understanding of their effective operation is incomplete. Scalability, data privacy and security, and interoperability between diverse systems and technologies are technical concerns. The requirement for real-time data processing increases the level of complexity. Incorporating these technologies into existing infrastructures necessitates meticulous planning and technological advances, with potential repercussions for existing systems. The regulatory environment must also adapt to these new technologies, which raises questions regarding deployment and operation regulations.

The purpose of this paper is to delve into the complexity of the 5G V2X digital twin architecture, which is a paradigm that is destined to determine the future of intelligent transportation systems. It is also to provide a full overview of many aspects of this cutting-edge technology by doing a thorough investigation into this area. Finally, it presents the wide variety of applications that are made possible by this technology in the hopes of illuminating the transformational potential that it possesses in several subfields of transportation. The principal contributions are:

- Developing requirements for a 5G V2X Digital Twin architecture, ensuring user requirements, 5G infrastructure, and numerous V2X communication modalities are understood and integrated.
- Developing a novel architectural framework for a 5G V2X system, defining roles, interactions, data flows, and component specifications to create an effective, integrated system.
- Highlighting challenges and open issues in designing a 5G V2X Digital Twin, including assuring ultra-reliable, low-latency communication, optimizing resource management, and addressing privacy and security concerns.

2 RELATED WORK

This section provides an overview of the existing research relevant to the 5G V2X digital twin architecture. The discussion encompasses the incorporation of 5G technology,V2X communication, and digital twin technology within the extant state-of-the-art research. The primary objective is to gain a comprehensive understanding of the current landscape, identify gaps in the existing architectures, and discuss how previous studies have addressed similar problems or obstacles. This endeavor will enable us to precisely position our work within the broader scientific context and demonstrate the advancements our proposed architecture brings to the discipline.

Mario H, et. al. [9] provided a comprehensive introduction to the 5G NR V2X standard, with a specific focus on various aspects such as sidelink, physical layer, resource allocation, service management, Uu interface enhancements, mobility management, and co-existence mechanisms between 5G NR V2X and LTE V2X. The authors also discussed use cases, system architecture, and evaluation methodology. However, their study primarily addressed simulation assumptions rather than delving into the realm of digital twins.

Huan X, et. al. [14] conducted a comprehensive examination and discussion on the potential of utilizing artificial intelligence to harness the capabilities of digital doppelgangers in the context of 5G networks and beyond. The authors highlighted the increasing adoption of the digital twin concept in various industries, including smart manufacturing, oil and gas, construction, bio-engineering, and automotive, as part of the ongoing digital transformation.

In [16], a methodology was presented for the creation and utilization of Mobile Networks Digital Twins (MNDTs), with a particular emphasis on the B5GEMINI project. The B5GEMINI project seeks to develop an MNDT for 5G core settings and 6G progression, thereby enabling applications in advanced scenarios such as cybersecurity and Industry 4.0. However, the study does not provide a comprehensive explanation of the construction of the 5G network using digital twin technology.

Haozhe, et. al [20] designed a flexible DT for network slicing to monitor performance metrics at the slice level across diverse network configurations. The proposed DT employs a non-Euclidean graph neural network model that can directly extract knowledge from segmented network representations. Experimental results demonstrate that the DT can accurately simulate network behavior and predict end-to-end (E2E) latency across a variety of topologies and unknown situations.

In [17], Mariana and Joaquin discussed the construction of DTs with a specific focus on the methodological design, creation, and connection of physical and virtual objects. The study investigates various aspects, including the selection of functional requirements, architecture planning, integration, verification, real-time information exchange, and the use of experimental platforms for DT development.

Spirent Communications (LSE:SPT) [8] simplified 5G with network digital twin for numerous use cases. One such use case is Cellular (C-V2X) Virtual Drive Testing. Instead of driving miles, they developed a virtual platform to simulate complex what-if scenarios and environmental variables.This approach allows for the exploration of connected vehicle functionalities, including enhanced convenience, safety, and infotainment options. By utilizing the Digital Twin, drivers and passengers can test, refine, and optimize C-V2X communication. However, the platform is not open-source, and limited information is available regarding its compatibility with 5G communications.

To the best of our knowledge, no previous scholarly work has focused on the development of an open-source digital twin specifically designed for 5G V2X communications. The construction of such a digital twin holds significant value for both the industrial and academic communities, offering benefits and opportunities for research, development, and collaboration.

3 THE MAIN 5G V2X DIGITAL TWIN COMPONENTS AND REQUIREMENTS

Data security and privacy safeguards, a low-latency and high-speed 5G communication infrastructure, and a reliable data collection and input system are all necessary components of a digital twin architecture for 5G V2X connectivity. To create virtual duplicates in real time, we need a powerful computing platform with predictive analytics. In order to interact with and use a system efficiently, a streamlined user interface and visualization tools are required. These parts play a crucial role in facilitating reliable, effective, and smart communication between vehicles on the road [2, 22, 23]. The most important factors and prerequisites are as follows:

Sensing and Data Acquisition: is a vital component, which entails the use of sensors to collect important information about real-world items like cars and buildings. By collecting data from across a wide range of parameters, these sensors enable more precise forecasting and more efficient operations. Since this stage permits the incorporation of diverse data from multiple sensor sources, it is vital to comprehend the extensive impact it has on the digital twin architecture.

Data Ingestion and Processing: is another essential part of the digital twin. Sensor data from the real world must be brought into the system for analysis. Data is gathered, imported, processed, and stored in preparation for its use and analysis by the platform. Edge computing devices are crucial to this procedure because they allow for preliminary data processing to be carried out locally, saving time and bandwidth before data is sent to the digital twin platform. When initial data processing is done at or near the data source, the data is sent to the cloud or data center for additional processing.

The entire data-gathering and processing procedure must be able to handle data coming in at a constant rate in real time. Handling real-time data adds new layers of complexity to a digital twin architecture developed for 5G V2X communication, including the need to manage massive amounts of data, guarantee data integrity and dependability, and craft a bulletproof data ingestion and processing pipeline. Because of their scalability and reliability, cloud-based solutions are an integral part of the data input and processing phase.

The 5G Network: an open-source digital twin platform for 5G V2X communication relies heavily on the 5G Network. Due to the massive amounts of data and the requirement for real-time processing, it strongly depends on the 5G network for seamless and speedy connectivity. The digital twin platform can allocate network resources for specific activities thanks to the 5G network's advanced features including network slicing, beamforming, huge MIMO (Multiple Input, Multiple Output), and other 5G technologies.

Finally, the platform needs to be able to take full advantage of the 5G network, allowing it to handle massive amounts of data while facilitating smooth communication with a diverse set of devices. This calls for a carefully planned network layout that employs suitable standards and protocols to guarantee seamless interoperability and communication.

The Data Model: is the process of developing a logical framework for the collection, storage, retrieval, and analysis of data from the real world and its digital representation. Differentiating between simple and complicated models is the number of entities, systems, and subsystems involved.

A well-designed strategy for data collection, processing, and network design is essential to the development of a functional digital twin architecture for 5G V2X communication. When the digital twin platform is updated to take advantage of the specific characteristics of the 5G network, it can better adapt to the dynamic nature of the digital world. Building data models for digital twin platforms calls for in-depth knowledge of real-world systems and the skill to convey that knowledge in a digital setting. A more sophisticated model might be harder to manage and raise processing requirements, so finding a happy medium between the two is essential. However, a simplified model may not accurately reflect the complexity and dynamism of the actual system. Therefore, an efficient and accurate representation of the physical world requires careful preparation, in-depth domain expertise, and iterative refinement during the data model generation process.

The Simulation Engine: The digital twin platform's Simulation Engine is the brain of the operation. Data from the physical world is processed and organized in line with a data model, and the resulting model is used to describe the connections, patterns, and dynamics of the physical world. This ability is vital for many uses, including traffic forecasting and machinery upkeep planning. To make the simulation engine more effective and improve its ability to recognize complex patterns, make predictions, and adapt to changing conditions, cutting-edge technologies such as artificial intelligence (AI) and machine learning (ML) can be incorporated [1].

Building an AI/ML-powered simulation engine that works well requires extensive knowledge of data science, AI, software engineering, and the physical systems being modeled. Large amounts of data and complicated models may need to be processed in real time during these simulations, which places heavy demands on the computer resources available. Therefore, it is crucial to carefully plan and construct the simulation engine, which involves doing things like picking the correct technologies and tools, optimizing performance, and making sure the simulations are accurate and reliable.

Data Storage and Management: The ability to store and manage large amounts of data is essential for a digital twin platform. For complicated systems like a city's transportation network, digital twins produce massive amounts of data that must be stored safely, maintained effectively, and quickly accessed. Data requirements and characteristics will dictate the database, data structure, and algorithm selections. The cost, performance, and security of your data are all affected by whether it is stored on-premises or on the cloud.

User Interface and Visualization: The digital twin platform's user interface and visualization tools are integral to its success. Poor design, on the other hand, can make even the simplest tasks difficult and tedious for users by making complicated data and interactions less intimidating. Users' technical knowledge, roles, and the tasks they need to do when using a digital twin platform should all be taken into account while designing the interface and visualization elements of the platform. Methods of user-centered design such as user persona creation, storyboarding, and usability testing can be useful in this respect.

Security and Privacy: It is critical to adopt robust security measures across all levels of a digital twin platform because of the sensitive nature of the data being handled. Secure data transfer uses encryption and secure communication protocols to prevent data from being intercepted or tampered with while it travels from the physical world to the digital twin. To guarantee that only authorized users have access to data or can carry out certain actions, access control methods are crucial in digital twin platforms. User authentication methods, role-based access control systems, and privacy measures are all examples of procedures that can be used to keep information secure and private. Since a digital twin platform may collect and manage PII (Personally Identifiable Information), privacy is another crucial factor to think about in its development. Building a safe and private digital twin platform requires a multi-faceted strategy that includes both technical and policy/procedure components.

Interoperability and standards: To ensure a smooth interaction between the digital twin platform and other systems and components, interoperability and standards are essential. The platform's features and capabilities will be more widely available and useable if it is compliant with applicable standards, allowing for easier interaction with other systems and the sharing of data and information. In order for external systems to collect data, start operations, or respond to events from the digital twin platform, an API (Application Programming Interface) must be created.

The Analytics and Decision Support: Extracting value from the massive amounts of data collected is a crucial function of a digital twin platform, and this is where analytics and decision support come in. The main goal of a digital twin is to help in learning, forecasting, and decision-making, not only to produce a digital copy of a physical system. Finding patterns, trends, and links in data requires the use of sophisticated data analysis tools including statistical analysis techniques, machine learning algorithms, and optimization approaches. In contrast to more traditional modeling techniques, machine learning algorithms may learn from data, improve their performance over time, and deal with complex, non-linear interactions.

Predictive models can foretell the system's future state based on present and historical data, while prescriptive models can prescribe measures to optimize a desired outcome. Both types of models can be developed using machine learning. A digital twin of a city's transportation network might utilize machine learning to predict traffic congestion based on real-time data and historical trends, then recommend alternate routes to save travel times.

Having robust analytic resources, however, is not enough. The digital twin platform needs to incorporate these tools so that they can be used to maximum benefit when making decisions. To achieve this goal, analytical data must be presented in a straightforward fashion, decision-support capabilities must be made available, and users must be given the freedom to experiment with various scenarios and their potential effects.

Users may make the most of the digital twin and utilize it to make informed decisions with the help of the Analytics and Decision Support feature. By improving in these areas, digital twin systems will be more adaptable and widely used, allowing for the fusion of a wide variety of data sources and analytical tools.

4 THE PROPOSED DIGITAL TWIN ARCHITECTURE FOR 5G V2X COMMUNICATION

The 5G V2X Digital Twin is instrumental in advancing connected vehicles and intelligent transportation systems. It precisely simulates the V2X system's many elements, capturing everything from vehicle attributes and communication networks to environmental contexts and traffic scenarios. This simulation closely mirrors the complexities of 5G network standards, data transfers, and potential disruptions, ensuring the virtual representation aligns with real-world conditions.

The digital twin's primary purpose is to enable researchers and developers to forecast and fine-tune V2X network operations. This foresight is pivotal for anticipating traffic patterns, streamlining routing, boosting fuel efficiency, and augmenting safety protocols. This digital counterpart permits risk-free testing of diverse scenarios, paving the way for safer, real-world implementations.

Figure 1 outlines the architectural blueprint for the 5G V2X Digital Twin. Central to its design is a microservices-based structure, ensuring system scalability, reliability, and interoperability. Cloud-native technologies amplify their capabilities, while RAID configurations and fault-tolerant measures uphold data integrity. Standard communication protocols and RESTful APIs guarantee seamless connectivity. The system adapts via AI and machine learning, and robust security mechanisms—including end-to-end encryption, intrusion detection, and thorough testing—fortify its defenses. Privacy is fortified using differential privacy methods and strict access controls. Open-source platforms, like TensorFlow and Apache Kafka, provide adaptability and a wealth of community expertise. By merging Multi-access Edge Computing (MEC) with DSRC protocols, the architecture optimizes communication, blending 5G's swift responsiveness with V2X-specific requirements.

4.1 5G V2X Physical Twin

The 5G V2X Physical Twin includes various technology enhancements designed to improve communications between vehicles, pedestrians, and infrastructure elements. The communication occurs over two interfaces - PC5, used for direct communication (sidelink), and Uu, the regular cellular link. The PC5 interface facilitates direct V2X communication between UEs (User Equipment), bypassing the base station, enabling low latency, high reliability communications, making it especially beneficial for safety-critical V2X services.

The 5G system architecture for V2X communication includes other key network elements like the AMF (Access and Mobility Management Function), UPF (User Plane Function), SMF (Session Management Function), and PCF (Policy Control Function). These elements interwork to ensure effective V2X services and consider both standalone (SA) and non-standalone (NSA) operation modes, ensuring compatibility with various deployment scenarios.

V2I Communication is a fundamental part of the V2X network system, focusing on the interaction between vehicles and road infrastructure. V2I communication enables various functionalities like red-light violation warnings, reduced speed zone warnings, and curve speed warnings, enhancing road safety. With the progression towards smart cities and intelligent transportation systems, V2I

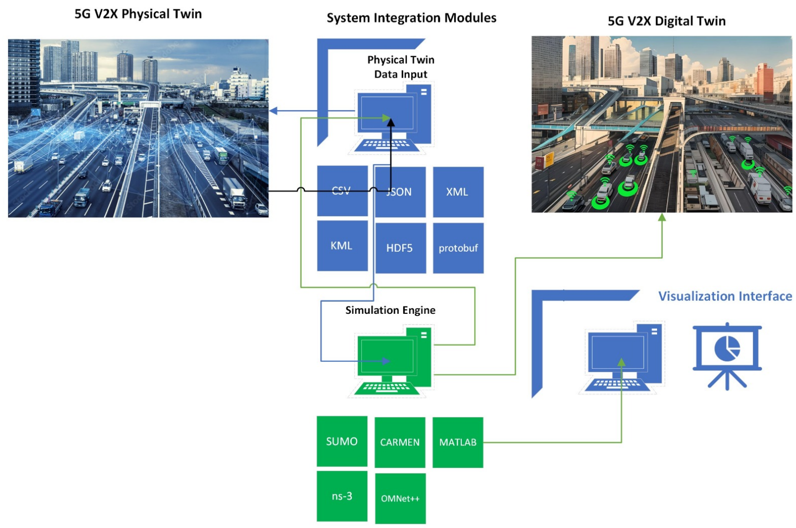

Figure 1: 5G V2X Digital Twin Architecture.

communication is likely to play an even more significant role, enabling traffic signals to adjust their timing based on real-time traffic flow, improving traffic management and reducing congestion.

V2N communication involves automobiles communicating with 5G cellular towers and servers. V2N connectivity makes vehicles part of a larger ecosystem, enabling remote system monitoring, predictive maintenance, and personalized services. 5G networks improve system efficiency and responsiveness with high speed and low latency. V2P technology, based on high-speed, dependable, and low-latency 5G networks, can improve urban vehicle-pedestrian safety. V2P communication in the 5G V2X framework ensures transportation safety and efficiency.

Vehicle-to-Cloud (V2C) communication enables remote software upgrades, fleet management, entertainment, and predictive maintenance. 5G networks enable advanced V2C services like remote software upgrades, fleet management, infotainment, and predictive maintenance by storing, processing, and retrieving massive amounts of data from the cloud.

A 5G V2X network digital twin can help predict traffic congestion, optimize traffic light timings, and improve vehicle safety. The digital twin can leverage real-time data from car sensors, local infrastructure, and other vehicles to make connected vehicles and the V2X network safer for drivers, passengers, and pedestrians.

Due to the volume and sensitivity of data shared, V2X networks are appealing targets for hackers. Data security and privacy are vital to their design. Encryption, secure network protocols, intrusion detection systems, and firewalls should be built into the system to prevent unauthorized access and maintain its integrity.

Data anonymization removes or encrypts personally identifying information and implements frequent audits and assessments to discover vulnerabilities and ensure up-to-date security. Data breaches should be addressed quickly using disaster recovery and incident response procedures.

4.2 System Integration and 5G V2X Digital Twin

Tools and technologies are needed to implement system integration for a digital twin of a 5G V2X network with other systems of urban infrastructure, such as smart city data systems and Internet of Things (IoT) devices. Internet of Things platforms, application programming interfaces, data integration tools, middleware, data format standards, cybersecurity instruments, interoperability frameworks, and container orchestration instruments are all examples. Tools must be selected carefully to ensure they meet the requirements of the system and the ecosystem into which it will be integrated. Real-time information from a physical V2X network is essential to the functioning of a digital twin. Vehicle-based sensors, on-board sensors, road conditions, traffic data, and data from wider network sources including 5G cellular towers, satellites, and cloud servers are all sources for this information. Insights regarding traffic patterns, road conditions, weather shifts, and infrastructure components can be gleaned from these data sets.

The file formats used to feed data into a digital twin of a 5G V2X network are context and system design dependent. Comma-separated values (CSV), Java Object Notation (JSON), eXtensible Markup Language (XML), Keyhole Markup Language (KML), Hierarchical Data Format 5 (HDF5), binary formats, and protobuf (protobuf) are all common data formats.

The simulation engine is the brain of the digital twin, and it is in charge of reproducing the V2X network's actions and reactions based on the provided information. Its primary role is to digitize the stream of real-time information coming from the V2X network's physical nodes. Vehicle dynamics, communication protocols, traffic flow dynamics, and network behaviors are only some of the many characteristics of the V2X network that are captured by the engine's different algorithms and models. These intricate interactions are then computed in a simulated setting, which acts as a digital analog to the real-world V2X network.

The simulation engine can not only replicate the current status of the V2X network but also anticipate future possibilities depending on the available information. This foresight into future operational difficulties, performance bottlenecks, or safety risks before they manifest in the actual network is a great asset. Developers can anticipate and prevent problems and create ideal methods by examining multiple "what if" scenarios.

To generate a trustworthy digital twin, the simulation engine needs to be flexible enough to incorporate new information and adjust its models accordingly. This guarantees that the digital twin will always accurately mirror the underlying physical network, regardless of how the V2X network changes over time.

Vehicle-to-everything (V2X) network environments can be simulated with the help of a number of widely-used software tools and simulators. Here are a few: MATLAB, Simulink, ns-3, OMNeT++, SUMO (Simulation of Urban Mobility), and CARMEN (Carla simulation for multi-agent reinforcement learning). Various factors, such as the complexity of the network and the types of scenarios to replicate, should be taken into account when deciding which simulator to use for the digital twin. Digital twins that employ predictive analytics and machine learning have the potential to greatly expand the V2X network's usefulness. Machine learning algorithms find rich ground in the mountains of real-time and historical data collected from disparate sources across the V2X network.

With the use of machine learning, the digital twin can analyze these data patterns and foresee potential problems with the system, such as traffic jams, slow networks, or broken vehicles. This foresight has great potential to improve proactive decision making and V2X network optimization.

The digital twin provides multiple opportunities for applying machine learning models to enhance the functioning of the system. Intelligent traffic management systems, for instance, can be taught to apply reinforcement learning algorithms to improve signal timing in response to actual traffic conditions. Based on driver behavior and the surrounding environment, supervised learning algorithms can estimate the likelihood of traffic accidents. Complex tasks like object identification and recognition can benefit greatly from the use of deep learning models, which is essential for enhancing security in V2X networks.

Several resources and platforms are available for integrating predictive analytics and machine learning into a digital twin for a 5G V2X network. Python, R, MATLAB, Apache Spark, H2O.ai, RapidMiner, Weka, TensorFlow Extended (TFX), and DataRobot are just a few examples.

4.3 Visualization Interface

The visualization interface is a crucial component of a digital twin, providing users with an interactive representation of the V2X network's inner workings. It converts raw data and insights into visual formats, including real-time maps and graphs to help identify trends and anomalies. A digital twin can be built with various software packages, such as Tableau, Power BI, QlikView/Qlik Sense, D3.js, Plotly, Leaflet/Mapbox, Kibana, Dash, Bokeh, and MATLAB/Simulink. The efficiency, dependability, and safety of the V2X network are enhanced by the digital twin's utilization of these assets.

When selecting a tool to assess the performance and usefulness of a digital twin system, factors such as data complexity, interaction, and programming languages must be considered. Key performance indicators include prediction precision, system responsiveness, data latency, data throughput, and network dependability. High prediction accuracy is crucial for machine learning algorithms and data usefulness.

Response time and data latency are vital parameters for a real-time system like a V2X network. Low reaction and data latency times indicate high-performing, efficient systems, while network dependability ensures continuous performance even under severe loads or tough situations. Monitoring and analyzing the performance of a digital twin system involves various tools, including Prometheus, Grafana, Zabbix, network monitoring tools, log analysis tools, data analytics platforms, AI and machine learning platforms, cloud platforms, and automated testing tools. The selection of these tools depends on the specific requirements of the system, the infrastructure it operates within, and the defined key performance indicators.

5 DISCUSSION AND OPEN ISSUES

Table 1 highlights the main comparsion features of the proposed architecture with the related 5G V2X digital twin architectures.

A thorough comprehension of the 5G Vehicle-to-Everything (V2X) digital twin is necessary due to the system's complexity. Various parameters must be adequately portrayed, including the vehicle's speed, direction, environment, and probable traffic conditions. A deep familiarity with both 5G and V2X technologies, as well as a keen eye for detail, are essential for developing a 5G V2X digital twin. The huge amount of data generated by these simulations is another obstacle that calls for effective data management techniques.

Data privacy and security: The development of a 5G V2X digital twin relies heavily on data privacy and security. In order to run reliable simulations and make reliable predictions, it is necessary to collect and process a large quantity of data, such as technical requirements, performance measurements, and private information about users' habits and routines. In order to keep users' trust and meet applicable rules, this information must be saved and handled securely.

Cybersecurity: the increased interconnectedness that comes with a 5G V2X system also increases the potential for cyber threats, therefore cybersecurity and data privacy are inextricably linked issues. Users' privacy might be compromised, the V2X system's functionality jeopardized, and actual damage could be inflicted if an assault were to be successful. As a result, stringent cybersecurity safeguards must be incorporated throughout the entire process of creating and using the digital twin.

Real-time data processing: the backbone of a 5G V2X digital twin system is real-time data processing, which receives continuous input from a wide variety of sources, such as Internet of Things (IoT) sensors in vehicles, traffic infrastructure, and other digital twins. The state of the twin must continuously consume, process, and reflect this data in order to give accurate simulations and predictions. Fast processing is important, but so is checking that the information is reliable and correct.

A robust computational infrastructure, including high-performance servers, sophisticated data analytics platforms, and state-of-the-art network technology, is required to meet these difficulties. Edge computing and other technologies can assist minimize latency and

Table 1: The comparison features of the related 5G V2X digtial twin architecture.

Architecture	Scalability	Reliability	Interoperability	Adaptability	Security Privacy	Open Source	Main focus (5G / V2X / Both)
[8]	No	Yes	No	Yes	Yes	No	Both
[7]	No	Yes	No	Yes	Yes	No	5G
[16]	Yes	Yes	Yes	No	Yes	Yes	5G
[4]	No	Yes	No	No	Yes	Yes	V2X
[20]	No	Yes	No	No	Yes	Yes	5G
[5]	No	Yes	No	No	Yes	No	V2X
[10]	No	Yes	No	No	Yes	No	Both
Proposed Architecture	Yes	Yes	Yes	Yes	Yes	Yes	Both

allow for real-time data processing, while machine learning and artificial intelligence methods can quickly and accurately process and understand the data. The development and deployment of a 5G V2X digital twin necessitates the ability to scale. Expanding the digital twin's representation of the physical world necessitates increasing the digital twin's own size. If this doesn't happen, the system could get overloaded with information and suffer performance drops or even crash.

Scalability: A 5G V2X digital twin system must be scalable in order to accommodate the introduction of new components, the evolution of the running environment, and the development of novel applications. New technology, shifts in the operational environment, and adjustments to traffic management methods should all be easily incorporated into a digital twin system. Modularity, cloud-based solutions, open standards, and predictive analytics are all examples of scalable design architecture.

Modeling and simulation accuracy: Predictive analyses, proactive decision-making, and scenario simulation are all made possible with high-fidelity modeling and simulation, making them indispensable for developing a 5G V2X digital twin. However, there are several obstacles to overcome when attempting to mimic the actual world and accurately portray it in a digital setting, such as communication and traffic infrastructure, pedestrians, and the Internet of things. The development of a viable digital twin that faithfully simulates V2X communication settings relies on accurate modeling of these aspects.

5G network coverage and infrastructure: A 5G V2X digital twin require widespread availability of 5G networks and associated equipment. Massive data volumes and the need for real-time communication rely on a solid 5G network as their foundation. Lacking complete coverage, the digital twin risks inaccurately simulating the environment and interactions of its physical counterpart due to data gaps, latency difficulties, or discrepancies. The fact that the performance of a 5G network can vary depending on factors including network congestion, signal strength, interference, and geographical and structural issues is also crucial.

In order to successfully build and run a 5G V2X digital twin, it is necessary to construct a digital twin on the foundation of 5G infrastructure. A system architecture that is agile and adaptive enough to accept changes in the underlying 5G infrastructure is essential if the digital twin is to keep pace with its own evolution.

Integration: Integrating with other technologies such as artificial intelligence, machine learning, the internet of things, and edge computing is crucial for a 5G V2X digital twin to function well. The digital twin can benefit from the special features offered by these technologies. However, because to variances in data formats, connection protocols, and processing needs, integrating various technologies into a coherent system is a substantial problem.

Risk testing and validation: Since a digital twin's primary goal is to produce an exact reproduction of the real world, risk testing and validation: are crucial steps in the development process, with far-reaching implications for safety, efficiency, and more. Any flaws or mistakes in the digital twin could have negative effects in the actual world.

For a 5G V2X digital twin system to be successful, it must be scalable, modelable, simulatable, and interoperable with other technologies. The digital twin can be a useful tool for testing, optimizing, and decision-making in the V2X domain if the hurdles are overcome and the technology is allowed to mature. The capabilities of a 5G V2X digital twin in terms of modeling and simulation, data processing and analytics, scenario response, and behavior under different operational conditions must all be tested. These examinations are difficult in their own right and may necessitate novel resources, approaches, and knowledge. After testing, the digital twin is validated to ensure it performs as expected and conforms to predefined criteria. This can include verifying prediction skills, assessing performance in real-world use cases, and comparing simulated results with actual data.

Regulatory considerations: The security, dependability, and efficiency of the 5G V2X digital twin depend heavily on adherence to applicable regulations. Organizations working on and deploying 5G V2X digital twins face an unpredictable and shifting regulatory landscape due to the newness and quick development of the industry. The collecting, processing, and storage of massive volumes of sensitive or personal data are at the heart of digital twins, making data privacy and security paramount. The ever-evolving nature of cybersecurity threats makes it all the more important to adhere to data protection standards.

The digital twin's regulatory implications for use and implementation are also crucial. There will certainly be more attention paid to the accuracy, reliability, and potential influence of digital twins as they become more embedded in the decision-making process. Like other safety-critical systems, digital twins may eventually be subject to regulatory standards governing their design, development, and deployment. It is essential for businesses operating in the digital twin market to navigate these prospective rules and keep up with their evolution.

6 CONCLUSION AND FUTURE WORK

The combination of digital twin technology and 5G Vehicle-to-Everything (V2X) connectivity has promising implications for the modernization of transportation systems and the growth of smart cities. The first step in laying the foundation for a 5G V2X digital twin framework is to construct a digital, real-time replica of the physical world. This replica must contain detailed information regarding all aspects of vehicular communication, as well as street configurations and traffic conditions. Using the low latency, high bandwidth, and massive machine-type communications that 5G will provide, the accuracy of the digital counterpart will be enhanced to make it a more effective tool for predictive analytics, simulation, and system optimization.

To effectively construct this framework, it is necessary to devise an appropriate data collection and processing strategy. Onboard sensors and 5G-connected devices perpetually generate a vast amount of data in real time, necessitating a data intake system that is both efficient and scalable. This information must be processed without delay. In addition, it is necessary to construct and implement an analytics layer using machine learning and artificial intelligence techniques. This will facilitate comprehension and anticipation of complex traffic patterns. In addition, the digital duplicate should be able to self-teach, adapt to various aspects of its environment, and improve its accuracy over time.

Essential to the efficient operation of a 5G V2X digital twin infrastructure is the safeguarding of user information and their right to privacy. In proportion to the number of connected devices that are incorporated into the transportation system, its susceptibility to intrusions will increase. In order to safeguard sensitive data from potential threats, it is necessary to implement an effective security plan. In addition, a robust data governance system is required to ensure the correct utilization and sharing of data while adhering to privacy regulations.

A 5G V2X digital twin framework provides an unprecedented opportunity to envision and shape the future of transportation. If we take advantage of the promise offered by 5G technology and integrate it with digital twin technology, we will be able to design transportation systems that are not only safer but also more efficient and more environmentally friendly. To truly realize this potential, however, the challenges of data management, analytics, and security must be aggressively addressed. To further enhance this technology and pave the way for a truly intelligent city, additional research and development work is required.

ACKNOWLEDGEMENT

The work of Mehdi Sookhak was supported by the National Science Foundation (NSF) under grant number CNS-2318725 and the US Department of Transportation (USDOT) Tier-1 University Transportation Center (UTC) Transportation Cybersecurity Center for Advanced Research and Education (CYBER-CARE). (Grant No. 69A3552348332).

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