Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

**Request for Information on the National Digital Twins R&D Strategic Plan**

Hashim Shaik
Irene Tsapara

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[redacted]

Melissa Cornelius
[redacted]
July 25, 2024

Re: RFI Response: Digital Twins R&D Plan

Dear Ms. Cornelius,
On behalf of the National University, we are pleased to submit our response to the Request for Information (RFI) on the National Digital Twins R&D Strategic Plan. Our institution has extensive experience in [relevant field], and we believe our insights will contribute significantly to its development.
We appreciate the opportunity to provide input and look forward to collaborating further on this important initiative.

Sincerely,

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Ph.D Candidate
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**Digital Twin Representation of Foliage Through Computer Vision, Aerial Image Analysis and Machine Learning techniques to enhance the Network Planning and Deployment Problem**

In telecommunications, the emergence of millimeter-wave (mmW) networks is a pivotal development aimed at fulfilling the surging demand for greater bandwidth, enhanced throughput, and minimized latency (Abdullah et al., 2020; Hong et al., 2021). This progression is vital for the progression of 5G wireless networks to meet the escalating needs of the mobile industry. However, mmW networks are challenged by issues like signal scattering, atmospheric absorption, and the obstruction caused by foliage and building structures; these are critical to navigating the successful roll-out of 5G networks, ensuring optimal coverage and data speeds. (Barb et al., 2022; Bose et al., 2024; N. A. Khan & Schmid, 2024; Pradeep et al., 2021; Y. Zhang et al., 2019).

The process of accurately capturing foliage data, crucial for the deployment of high-frequency networks like mmW, has traditionally relied on costly and time-consuming methods such as Light Detection and Ranging (LiDAR) and unmanned aerial vehicles (UAVs) (Q. Chen et al., 2022). However, the dynamic nature of our surroundings and the need for frequent data updates make traditional methods less viable for continuous application (Gaspari et al., 2022). In contrast, digital twin technology, with its adaptability and versatility, offers a groundbreaking alternative (Attaran & Celik, 2023)

Digital twins have emerged as a game-changing strategy with applications across various sectors, including urban development and industrial operations, particularly in the planning of wireless networks (T. Deng et al., 2021; Gabriele et al., 2023). One of the most promising applications of digital twin technology is in the detailed modeling of foliage or vegetation. By creating a virtual representation of the natural environment, focusing on the variety, distribution, and properties of plant life, digital twins provide network planners, environmental experts, and other stakeholders with a comprehensive understanding of how vegetation influences signal behavior, including path loss and network coverage, in high frequency mmW networks crucial to 5G and 6G technology (L. et al., 2022; Kuruvatti et al., 2022).

The sample image (Figure 1) depicting a digital twin representation of an urban area has been created for illustration purposes. It includes 3D models of buildings, streets, and foliage, presenting a clean and simplified city landscape that could be used for architectural visualization or city planning simulation. The design conveys a modern and futuristic tone, indicative of advanced urban planning and smart city concepts (T. Deng et al., 2021; Shahat et al., 2021).

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**Proposed Solution**

Accurate modeling of foliage's channel propagation is vital for wireless network design, particularly in rural, suburban, and urban environments. The blockage effects of foliage, especially at mmW frequencies, can be severe because of the comparable size of leaves and branches to the transmitted signal wavelength. Overcoming these challenges is crucial to developing reliable channel propagation models that effectively consider foliage's impact on wireless communication systems (Anzum, 2021; Chikhale et al., 2022; Lai et al., 2023). Network operators must consider all these factors while deploying mmW technologies (5G, 6G) to improve user coverage and throughput.

Currently, foliage data is acquired using costly methods such as UAVs and LiDAR, requiring substantial physical effort (Q. Chen et al., 2022; Hematang et al., 2022; Mazzacca et al., 2022; Shen et al., 2023; Suhaizad et al., 2023). The continuous growth and transformation of foliage necessitates regular data collection to keep information current. The impracticality of repeating these tasks for regular foliage updates becomes clear because of their high cost, labor, and resource intensity. A more cost-effective and efficient approach involves leveraging Google Street View and satellite images in conjunction with state-of-the-art computer vision, image analysis and machine learning models for object detection (Aikoh et al., 2023; Sun et al., 2023; Y. Zhao et al., 2023), presenting a promising way forward to address the challenges on collecting foliage or vegetation data.

As foliage is one of the main characteristics impacting the higher frequency like mmW network deployment, this study addresses the problem of providing foliage information by creating a digital twin (DT) of an environment with foliage with which network operators planning to deploy networks with higher frequency can use in their network planning to place the nodes at right locations for better coverage and user experience (Gabriele et al., 2023; Nguyen et al., 2021; Qi & Tao, 2018; Thuvander et al., 2022; D. Zhao et al., 2022).

The aim is to develop a sophisticated digital twin that mirrors the physical environment, particularly integrating detailed foliage information (Lai et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). The digital twin will serve as a critical tool for network operators, enabling them to estimate the path loss attributed to foliage within the context of high frequency mmW network planning (Lai et al., 2023). Such estimations are pivotal for optimizing network performance and reliability in environments where vegetation can significantly impact signal propagation (Farooq & Lokam, 2023; Pradeep et al., 2021; Y. Zhang et al., 2019).

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In order to accomplish this, a machine learning model based on computer vision will be used, which will be meticulously trained on a large dataset of foliage imagery. This model will employ advanced instance semantic segmentation techniques to identify and categorize foliage or vegetation within images. The study will dissect images into precise regions or objects using image segmentation, classification, and object detection methodologies (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023; Y. Zhao et al., 2023).

This approach enables a pixel-level analysis of each scene, facilitating a deeper understanding of the vegetative elements within the digital twin environment (Jiang et al., 2023; Savelonas et al., 2022). The study will explore the nuanced interactions between vegetation and signal propagation, offering network operators a robust framework for mitigating the adverse effects of foliage on mmW network signals (De Beelde et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). This comprehensive approach representing foliage in a DT aims to bridge the gap between theoretical network planning and the practical challenges of natural vegetation, fostering more resilient and efficient communication networks in the face of environmental obstacles.  The study will utilize aerial and street view imagery from broad geographic areas in the regions where building of digital twin takes place.

The following sources are used to collect the aerial (satellite) images and street view images:

1. Maps Static API from Google (Google Maps Platform Documentation | Maps Static API | Google for Developers) (Google for Developers Maps Static API, n.d.).

2. Street View Static API from Google (Google Maps Platform Documentation | Street View Static API | Google for Developers) (Google for Developers Street View Static API Overview, n.d.).

3. Google Earth (https://earth.google.com/web/)

a. The following open source, Open Street Map (OSM), Java Open Street Map (JOSM), is used to collect information on streets, roads, and building outlines.

4. Open Street Map (https://www.openstreetmap.org/)

5. Java Open Street Map (https://josm.openstreetmap.de/)

**Proposed Framework and Methodology**

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The framework for employing digital twin technology in enhancing mmW network planning and deployment pivots around the Cross-Industry Standard Process for Data Mining (CRISP-DM) process model (Blume et al., 2020; Hayat et al., 2023). This framework is specifically tailored to address the unique challenges posed by foliage in urban and suburban environments, which can significantly impact mmW signal propagation due to its high frequency and susceptibility to attenuation by physical obstacles, such as trees and dense vegetation (Barb et al., 2022; De Beelde et al., 2023; Rogers et al., 2020). The digital twin representation of foliage, built upon the CRISP-DM framework, is a foundational tool for simulating and analyzing the interaction between mmW signals and urban foliage, facilitating optimized network infrastructure placement and configuration. This initial phase is crucial for delineating the scope and objectives of the mmW network planning project, with a specific emphasis on understanding how foliage impacts signal integrity and network performance (Lai et al., 2023). The aim is to leverage the digital twin to simulate real-world scenarios, thus enabling network engineers to preemptively identify and mitigate potential signal interference or blockage caused by vegetation. Identifying the specific needs, such as improving telecommunications infrastructure, enhancing urban green spaces, or optimizing environmental conservation efforts, will dictate the direction of the subsequent phases.

The second phase involves an initial data collection and familiarization process. For foliage digital twins, this entails gathering high-resolution aerial and street view imagery (Aikoh et al., 2023), LiDAR data, and any available UAV survey data (Q. Chen et al., 2022). Understanding the types, densities, and heights of foliage within the proposed network area is essential for assessing potential mmW signal attenuation or reflection issues. The following Data collection phase is Data preparation. This phase prepares the data for analysis, which may involve cleaning, selecting subsets, constructing data sets, annotating, and formatting data to suit the modeling needs (Dutta & Zisserman, 2019). Given the complexity of urban environments and the diverse data sources involved, this stage is critical for ensuring that the inputs to the machine learning models are of high quality and appropriately structured for detecting and analyzing foliage (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023; J. Zhang et al., 2021; Y. Zhao et al., 2023). With the data prepared, various modeling techniques are applied to extract patterns and generate the digital twin representation. In the case of foliage, machine learning models such as convolutional neural networks (CNNs) or Mask R-CNN are employed to identify, classify, and analyze foliage from the aerial or street view imagery (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023). This involves training models on annotated datasets, selecting the most effective models, and tuning parameters to optimize accuracy and performance (Rezatofighi et al., 2019).

Before proceeding to full-scale deployment, the models and their representations need to be evaluated against predefined success criteria, such as accuracy, reliability, and usability in practical applications (Rezatofighi et al., 2019). This could involve comparing the digital twin outputs with ground-truth data from LiDAR or UAV surveys and assessing the model's ability to represent foliage in various urban scenarios accurately. The final phase involves integrating the digital twin into the mmW network planning and deployment workflow. This enables planners and engineers to visualize signal propagation in the context of urban foliage, identify optimal equipment placement, and anticipate potential maintenance or signal-boosting requirements. The deployment also includes mechanisms for updating the digital twin with new data, ensuring it remains a relevant and effective tool for mmW network optimization (Rogers et al., 2020). By focusing on the unique challenges of mmW network planning in environments with significant vegetation, the CRISP-DM-based digital twin represents a targeted approach to enhancing network reliability and performance. Through detailed simulation and analysis of foliage interactions with mmW signals, network planners can make informed decisions that optimize coverage and capacity while minimizing interference and attenuation, thereby ensuring robust, high-speed wireless connectivity in urban and suburban settings.

**Figure 1**
*Digital Twin Representation of Foliage – Example*

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The current approach focuses on constructing a digital twin model to represent foliage in various environments, leveraging cutting-edge computer vision and machine learning techniques. The flowchart in Figure 3 outlines the process for constructing a Digital Twin model of foliage, starting with the region of interest as the initial input.

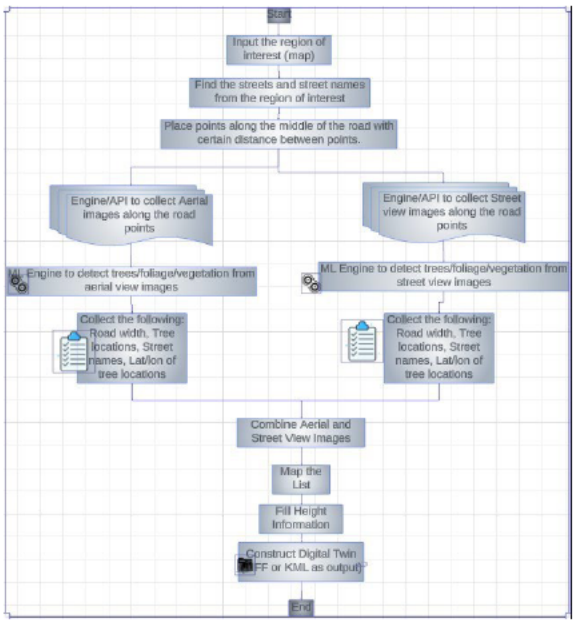
The significance of the digital twin representation of foliage primarily revolves around its pivotal role in advancing network planning and deployment strategies, especially pertinent to the challenges posed by urban environments on telecommunications infrastructure. This research is critical as it provides a novel approach to understanding and mitigating the impact of urban foliage on signal propagation, a significant concern for the deployment of high-frequency networks such as 5G and beyond (Barb et al., 2022; De Beelde et al., 2023; Lai et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). By creating virtual replicas of urban landscapes that accurately reflect the spatial distribution and physical characteristics of foliage (Attaran & Celik, 2023; Kuruvatti et al., 2022; Shahat et al., 2021), network engineers and planners can simulate and analyze how vegetation impacts network performance, leading to more informed decision-making and optimized network designs.

We want to provide a data-driven framework that can be used to improve the accuracy of predicting signal interference caused by foliage and thereby identifying the suitable locations for mmW node placements, which provides increased network coverage and user data connectivity (Abdullah et al., 2020; Pradeep et al., 2021; Y. Zhang et al., 2019). The research methodically applies machine learning and computer vision to create digital twins that serve as a sandbox for testing various network configurations and their interactions with urban greenery. This approach not only improves the reliability of network services in densely vegetated areas but also assists in identifying ideal locations for network infrastructure, minimizing environmental disruption and costs associated with physical trials (Rogers et al., 2020).

Several studies highlight the potential for digital twins to contribute to more sustainable urban development practices (Attaran & Celik, 2023; T. Deng et al., 2021; Kuruvatti et al., 2022; Shahat et al., 2021). The interaction between urban green spaces and network infrastructure can help planners design strategies that protect and enhance vegetation while ensuring technological advancement. Keeping this balance is essential for future smart cities since connectivity needs to be harmonious with the conservation of the environment and aesthetics in the urban context (Pradeep et al., 2021; Y. Zhang et al., 2019). The research enriches the data science literature by highlighting an innovative application of digital twins grounded in rigorous data analysis and modeling. It advances the telecommunications field by providing a novel tool for addressing one of the key challenges in network deployment (Bose et al., 2024; Pradeep et al., 2021), offering insights directly applicable to the design and optimization of next-generation wireless networks.

**Figure 2**

*Flowchart: DT Representation of Foliage (AI-Driven Foliage Detection Using ML & CV)*




### Business Case Analysis

Implementing a digital twin representation of foliage in urban areas offers a transformative approach to urban planning, environmental monitoring, and resource management. By leveraging advanced technologies like satellite imagery, street view images, and LiDAR data, this project aims to create a comprehensive and accurate digital model of urban vegetation. This business case analysis evaluates the research cost, the potential value and return on investment (ROI), and the cost and time required for implementation.

#### Timeline and Implementation of Digital Twin Representation of Foliage

| **Stage** | **Duration** | **Timeline** |
|---|---|---|
| **Stage 1: Data Acquisition** | 3 months | Month 1 - Month 3 |
| **Stage 2: Data Processing** | 4 months | Month 4 - Month 7 |

| | | |
|---|---|---|
| **Stage 3: Model Development** | 6 months | Month 8 - Month 13 |
| **Stage 4: Deployment** | 2 months | Month 14 - Month 15 |
| **Stage 5: Full Implementation** | 1 month | Month 16 |
| **Total** | 16 months | |

**Business Case Analysis Summary for Digital Twin Representation of Foliage**

| **Focus Area** | **Details** | **Cost** |
|---|---|---|
| **Foundational Research Cost** | | |
| Data Acquisition | Satellite imagery | $50,000 |
| | Street view images | $50,000 |
| | Other sources of data (LiDAR/UAV/OOKLA) | $100,000 |
| | **Total Data Acquisition Cost** | **$200,000** |
| Data Processing and Storage | Image processing software and tools | $75,000 |
| | Cloud storage & computational resources | $100,000 |
| | **Total Data Processing and Storage Cost** | **$175,000** |
| Research and Development | Personnel costs (data scientists, GIS specialists, software developers) | $500,000 |
| | Research materials and supplies | $50,000 |
| | **Total R&D Cost** | **$550,000** |
| Miscellaneous Expenses | Project management | $50,000 |
| | Contingency fund (10% of total cost) | $97,500.0 |
| | **Total Miscellaneous Expenses** | **$147,500.0** |
| **Total Foundational Research Cost** | | **$1,072,500.0** |

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**Summary**

This constructive research design aims to bridge the gap between theoretical computer vision techniques and practical applications in digital twin technology for foliage representation. This multidisciplinary approach, combining remote sensing, computer vision, machine learning, and digital twin technology, offers a comprehensive method for accurately representing foliage in digital models, which is essential for effectively planning and deploying next-generation wireless networks. The study seeks to offer a cost-effective, scalable, and accurate tool for urban planners and network engineers (Alkhateeb et al., 2023; Fett et al., 2023; Kuruvatti et al., 2022; Lehtola et al., 2022). The approach is grounded in rigorous data analysis, ethical considerations, and acknowledging its scope and limitations. It sets a foundation for future advancements in digital twin technology and its applications in innovative city development and environmental monitoring.

The current research significance of digital twin representation of foliage, utilizing computer vision image analysis methods, compared to traditional approaches like LiDAR and UAV, stems from its capacity to overcome inherent challenges and constraints in conventional methodologies. Traditional techniques such as LiDAR and UAV surveys are often cost-prohibitive (Rogers et al., 2020), labor-intensive, and require extensive human involvement for data collection and processing (X. Deng et al., 2022; H. Li et al., 2021). Moreover, these methods could be more extensive in their coverage, resolution, and ability to maintain up-to-date information. In contrast, the digital twin representation of foliage harnesses advanced computer vision, AI, and machine learning techniques to analyze aerial and street view imagery. This approach offers several advantages, including cost-effectiveness, scalability, and the potential for real-time or near-real-time data updates (Attaran & Celik, 2023; Mylonas et al., 2021).

By automating foliage detection and analysis, digital twin representation enables swift and accurate data collection, facilitating more efficient network planning, urban development, and other applications. The impetus behind developing a DT representation of foliage arises from the escalating demand for precise and current foliage information across diverse sectors, encompassing telecommunications, urban planning, and environmental conservation. Industry reports and white papers underscore the critical role of digital twin technology in optimizing telecommunications infrastructure and enhancing service quality (Alkhateeb et al., 2023; L. U. Khan et al., 2022; Kuruvatti et al., 2022). Several government initiatives, including ones aimed at sustainable urbanization and environmental stewardship, emphasize using digital twins to inform data-driven decision-making (Mylonas et al., 2021; Shahat et al., 2021).

Digital twins in urban and city planning will significantly displace traditional methods, like LiDAR and UAVs. The benefits include improved data integration, faster iterations, sustainability, and innovative city applications. AI and computer vision are driving the development of digital twins, which can be used to solve the challenges and limitations of conventional methods, offering more efficient, cost-effective, and scalable solutions.

References (Upon Request)