**The Digital Twin Representation of Foliage**

Dissertation Prospectus

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Hashim Shaik

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# Prospectus

## Introduction

In today’s rapidly advancing telecommunications landscape, 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. Yet, 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 these high-frequency networks, 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; X. Deng et al., 2022; Mazzacca et al., 2022; Rogers et al., 2020). To adapt to the dynamic nature of our surroundings, the need for frequent updates of data renders traditional methods less viable for continuous application (Rogers et al., 2020). However, the rise of digital twin technology offers a groundbreaking alternative (Attaran & Celik, 2023; Chang et al., 2021).

Digital twins have become a game-changing strategy with applications spanning urban development and industrial operations, notably in the planning of wireless networks (T. Deng et al., 2021; Gabriele et al., 2023). One of the most compelling uses of digital twin technology is in the detailed modeling of foliage or vegetation. By constructing a virtual representation of the natural environment, focusing on the variety, distribution, and properties of plant life, digital twins afford network planners, environmental experts, and other stakeholders a nuanced understanding of how vegetation influences signal behavior, including path loss and network coverage, in the context of high-frequency mmW networks integral to 5G technology (L. U. Khan et al., 2022; Kuruvatti et al., 2022).

The image (Figure 1) depicting a digital twin representation of an urban area has been created. 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 (Chang et al., 2021; T. Deng et al., 2021).

Figure 1

Smart City Digital Twin: Urban Planning and Green Spaces Integration

A city with many tall buildings

Description automatically generated

*Note.* This image was generated with the assistance of AI.

## Statement of the Problem

Connected devices are becoming more common, and users are demanding higher bandwidth, throughput, and lower latency. This led to the development of millimeter-wave (mmW) networks. The mmW band suffers from scattering, atmospheric absorption, canopy (foliage), and building facades. Implementation of 5G requires mmW band propagation channel optimization (Farooq & Lokam, 2023; Pradeep et al., 2021; Zhang et al., 2019).

Accurate modeling of foliage’s channel propagation is vital for wireless network design, particularly in diverse environments like rural, suburban, and urban settings. The blockage effects of foliage, especially at millimeter-wave 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; Chiehping et al., 2023; Chikhale et al., 2022). 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; Song et al., 2022; Suhaizad et al., 2023). 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 and machine learning models for object detection (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).

## Purpose of the Study

The purpose of this study is to build a digital twin of the physical environment containing foliage information that can be used by network operators for estimating path loss caused by foliage in high-frequency mmW network planning.

A trained computer vision based machine learning model on foliage imagery with instance semantic segmentation will be employed to determine whether foliage or vegetation is present in an image. Segmentation of images, classification, and object detection will be conducted, involving partitioning them into distinct regions or objects (Chen et al., 2021; He et al., 2018; Sun et al., 2023; Y. Zhao et al., 2023), enabling pixel-level understanding of the scene (Jiang et al., 2023; Savelonas et al., 2022).

This study will be conducted in Philadelphia, the United States of America. In the city of Philadelphia, Pennsylvania, it has been estimated that there are 2.9 million trees in the city, covering 20 percent of its area with greenery (Research Natural Areas, 2023; OCM Partners, 2024; Philadelphia LiDAR - LAS Files 2022 {2022} - Big Ten Academic Alliance Geoportal, 2022).

Images will be collected either from the aerial or street view image vendors (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.), and all the images will be annotated for the purpose of training a machine-learning model (Dutta & Zisserman, 2019). A fusion of aerial (satellite) and street view images will be performed for foliage estimation (Aikoh et al., 2023; Y. Zhao et al., 2023), followed by normalization, with a known reference object serving as a scale for measuring the presence of foliage or vegetation.

LiDAR or UAV datasets will be cross-referenced with measured foliage for model validation using regular grid divisions in the region of interest. The presence of foliage in both digital twin and LiDAR/UAV datasets will be assessed per grid, visualized with Venn diagrams. Mean Intersection over Union (MIoU) will be the primary metric, calculating the average intersection over union ratio to evaluate segmentation accuracy (Rezatofighi et al., 2019; Y. Zhao et al., 2023).

Future developments of Digital Twins will include elements such as building facades, traffic signs, and pedestrian crossings. Network operators will be able to use these DT models for efficient, intelligent network planning (Azad et al., 2019; Chang et al., 2021; Saravanan et al., 2022). This extension holds promise for various practical applications, contributing to the development of a better world and the realization of smart cities.

## Research Questions

The research questions aim to drive innovation and practical applications in the field of digital twin technology for foliage representation, fostering interdisciplinary collaboration and knowledge exchange among researchers, practitioners, and stakeholders. By addressing these research questions and hypotheses, the study aims to evaluate the feasibility, accuracy, and practicality of using digital twin technology for foliage representation, offering valuable insights for future research and practical applications in wireless network planning and environmental monitoring.

### RQ1

How can a digital twin effectively represent the spatial distribution and characteristics of foliage in natural environments?

### RQ2

How can the integration of image analysis of street view and aerial view images, coupled with computer vision techniques, provide a cost-effective alternative for obtaining foliage information compared to traditional methods?

### RQ3

How are the accuracy and performance of digital twin models for foliage representation compared to traditional methods such as LiDAR and UAV datasets, and what factors influence their effectiveness?

### RQ4

How can digital twin models incorporating foliage representation contribute to more effective urban planning, environmental monitoring, and wireless network optimization in smart city environments?

## Hypotheses

With the use of computer vision-based machine learning methods and image analysis techniques on images collected through aerial (satellite) and street view images, DT models can be generated that provide information about foliage so that mmW networks can be deployed more intelligently and efficiently with better information about foliage.

### H10

The DT generated through computer vision and image analysis approaches do not provide foliage information levels comparable to those obtained through more expensive LiDAR or UAV methods.

### H1a

The DT generated through computer vision and image analysis approach provides foliage information levels comparable to those obtained through more expensive LiDAR or UAV methods.

### H20

The DT generated through the integration of image analysis of aerial view and street view images, along with computer vision techniques, is not a cost-effective alternative for obtaining foliage information.

### H2a

The DT generated through the integration of image analysis of aerial view and street view images, along with computer vision techniques, is a cost-effective alternative for obtaining foliage information.

### H30

The accuracy of the digital twin is comparable to or worse than traditional methods like LiDAR or UAV datasets.

### H3a

The digital twin offers an accurate and dependable representation of various types of foliage, comparable to or at the level of precision achieved by traditional methods.

### H40

The Accurate foliage representation does not significantly contribute to more efficient and intelligent network planning.

### H4a

The digital twin's accurate foliage representation enhances the efficiency and intelligence of network planning, especially in high-frequency scenarios like 5G.

## Introduction to Research Methodology and Design

This section describes the research methodology and design for the study relating to the study problem, purpose, and research questions in constructing a Digital Twin Representation of Foliage. The constructive research design aims to bridge the gap between theoretical computer vision techniques and practical applications in digital twin technology for foliage representation. A constructive research design for the “Digital Twin Representation of Foliage” problem ensures a systematic approach to creating a practical solution that addresses the challenges of accurate foliage representation in digital twin models. Below (Figure 2) is a sample of a Digital twin representation of foliage (Z. Li et al., 2023; S. Song & Qin, 2022; Wilk et al., 2022).

Figure 2

Digital Twin Representation of Foliage - Example

A city with trees and buildings

Description automatically generated

*Note.* This image was generated with the assistance of AI.

The current approach focuses on constructing a digital twin model to accurately represent foliage in various environments, leveraging cutting-edge computer vision and machine learning techniques. Additionally, this section describes the population size, sampling approach, and sample size justification. This section also describes the instruments that are going to be used, information on their origin, and evidence of their reliability and validity. Furthermore, this section explains the data collection steps and the data wrangling procedure. This section then presents the strategies used to analyze the data and develop the models to test the research and answer the research questions. Finally, this section concludes with the study’s assumptions and summary. The flowchart below (Figure 3) outlines the process for constructing a Digital Twin model of foliage, starting with the region of interest as the initial input.

Figure 3

Flowchart: Digital Twin Representation of Foliage (AI-Driven Foliage Detection Using Machine Learning and Computer Vision)

A diagram of a computer

Description automatically generated with medium confidence

**Research Methodology**

**Data Collection**

To gather comprehensive data on foliage, high-resolution street view and aerial imagery are obtained using platforms like Google Maps, supplemented by LiDAR data for detailed three-dimensional foliage structure insights. The process involves leveraging Google's APIs to collect high-resolution street views and aerial images of the target areas (Figure 4), which serve as the primary data sources for identifying and analyzing foliage (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.). Additionally, LiDAR and UAV datasets of the same areas are obtained for validation purposes, allowing for comparison against the digital twin models created from Google imagery. This multi-faceted approach ensures robust and accurate representations of foliage within the digital twin framework.

Figure 4

Data Collection Strategy

A collage of a map

Description automatically generated

**Image Processing**

In the realm of image processing for foliage analysis, segmentation algorithms play a crucial role in distinguishing and classifying foliage from other elements captured within images. This involves employing advanced techniques such as edge detection, color analysis, and texture classification to accurately identify vegetation. Further steps include normalization and calibration of the collected images to address variations in lighting, scale, and perspective. This process often utilizes known reference objects within the images, enabling precise calibration for distance and height measurements. Additionally, image processing techniques are applied to extract salient features relevant to foliage, including tree canopy outlines, heights, and densities, thereby providing a comprehensive understanding of the vegetation in the analyzed area.

In the current research methodology, road width will be strategically utilized as a key reference object during the calibration phase, serving a critical role in accurately measuring the dimensions of surrounding objects, notably the heights of trees (Wang et al., 2018). This approach is grounded in the principle that road widths, which are typically standardized or can be accurately measured, provide a reliable scale against which the sizes of nearby objects can be gauged. By establishing the road width as a constant reference point, we can apply mathematical and imaging algorithms to extrapolate the dimensions of other entities within the image, such as trees (Yang et al., 2022). This process involves analyzing the proportional relationship between the known width of the road and the pixel dimensions of trees in aerial or street view images, thereby enabling the precise calculation of tree heights. This calibration technique is pivotal, as it ensures that our measurements of natural features within the environment are both accurate and consistent, laying a solid foundation for further analysis and the development of digital twin models that reflect the true characteristics of the physical world (Figure 5).

Figure 5

Measuring Unknown Objects from Known Reference Objects (From a Calibrated Image)

A coin and a few pills

Description automatically generated

*Note.*

Measuring the size of pills in an image by using USA Quarter coin as a reference object (Yang et al., 2022).

**Machine Learning Model Development**

Utilizing machine learning models, particularly deep learning frameworks like YOLOv3, YOLOv4, and Mask R-CNN, for instance, segmentation to distinguish individual trees and types of vegetation (J. Zhang et al., 2021). Overall, Mask R-CNN achieved the highest detection performance among the three algorithms, with superior results in terms of mAP, PBA, RR, and FLR (Table 1) (J. Zhang et al., 2021).

Table 1

Performance Metrics Comparison Among Mask R-CNN, Yolov3, Yolov4

| **Algorithm** | **mAP@IoU(0.5)** | **Mean Weighted Average (mWA)** | **Prediction Box Accuracy (PBA)** | **Recognition Rate (RR)** | **False Label Rate (FLR)** |
| --- | --- | --- | --- | --- | --- |
| Mask R-CNN | 84.21% | 86.82% | 88.76% | 84.97% | 3.6% |
| YOLOv3 | 70.08% | Not specified | Not specified | Not specified | Not specified |
| YOLOv4 | 78.28% | Not specified | Not specified | Not specified | Not specified |

*Note.* (J. Zhang et al., 2021).

The process begins with the preparation of training data, where images are annotated using tools like VGG Image Annotator (VIA) (Dutta & Zisserman, 2019) to identify both foliage and non-foliage elements, thereby creating a labeled dataset essential for the training of the model. Following this, an appropriate computer vision model is selected; options include Convolutional Neural Networks (CNNs) and Mask R-CNN, which are particularly adept at detecting and segmenting foliage from the surrounding urban landscape (J. Zhang et al., 2021). The final step involves the validation and testing of the models, using data from LiDAR and UAV as ground truth to confirm the accuracy of the foliage representation generated, ensuring that the machine learning models are effectively distinguishing and accurately representing foliage in the digital twin environment.

**Digital Twin Construction**

The integration of processed imagery and machine learning outputs is pivotal in crafting digital twins that prioritize precise depictions of foliage's spatial distribution and physical attributes (Cureton & Hartley, 2023; Somanath et al., 2023). This process entails merging the processed data from aerial imagery with the outputs of machine learning models to construct a holistic digital twin model that encompasses intricate foliage representation. Additionally, the refinement of the model is essential, involving iterative adjustments based on feedback garnered from validation procedures. This refinement phase includes fine-tuning machine learning models to enhance accuracy and detail in the representation of foliage within the digital twin environment (Z. Li et al., 2023; S. Song & Qin, 2022; Wilk et al., 2022).

**Validation and Benchmarking**

The comparison between digital twin models and LiDAR/UAV data for accuracy assessment involves several key steps. Firstly, LiDAR and UAV data are utilized as ground truth benchmarks to evaluate the fidelity of digital twin models in representing foliage. This benchmarking process serves as a crucial means of assessing the accuracy of the digital twin representations.

Quantitative comparison is facilitated through the application of accuracy metrics such as Mean Intersection over Union (MIoU) and Root Mean Square Error (RMSE) (Q. Chen et al., 2022; Hematang et al., 2022; J. Zhang et al., 2021; Rezatofighi et al., 2019; Rogers et al., 2020). These metrics provide objective measures for evaluating the performance of digital twin models in capturing foliage characteristics accurately. Specifically, the accuracy of foliage detection by machine learning models is scrutinized to ensure it meets predefined criteria. Performance metrics like Precision, Recall, F1-score, and Intersection over Union (IoU) are employed to assess the success criteria (Rezatofighi et al., 2019), with the IoU method being particularly instrumental in evaluating model inference results for foliage identification (J. Chen et al., 2021; Sun et al., 2023; J. Zhang et al., 2021; Y. Zhao et al., 2023).

Furthermore, the comparison between LiDAR/UAV datasets and measured foliage is conducted to validate the accuracy of the digital twin models. This validation process involves dividing the region of interest into regular grids and determining the presence of foliage for each grid in both the digital twin and LiDAR/UAV datasets. Venn diagrams are then utilized to visualize the intersection of foliage data, with an intersection percentage exceeding 80%, indicating accurate foliage measurement by the digital twin. Moreover, an analysis of influencing factors is undertaken to identify and scrutinize elements that may affect the accuracy of digital twins. Factors such as image resolution, processing algorithms, and diversity in model training data are examined to gain insights into their impact on the accuracy of digital twin representations (Figure 6).

Figure 6

Digital Twin Representation of Foliage Success Criteria

A diagram of a diagram of a variety of circles

Description automatically generated with medium confidence

**Population and Sample**

The study concentrates on urban regions with diverse vegetation coverage, encompassing densely populated cities and suburban areas to capture a broad spectrum of foliage types and urban configurations. Sample locations are chosen based on the accessibility of high-quality satellite and street view imagery, and LiDAR data. These selected sites within cities renowned for their substantial foliage diversity guarantee the inclusion of various vegetation densities and types in the study's analysis (OCM Partners, 2024; Philadelphia Lidar - LAS Files 2022 {2022} - Big Ten Academic Alliance Geoportal, 2022).

**Materials and Instruments**

* Imagery Sources: High-resolution Google Street View and aerial images (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.).
* Google Maps API for collecting street views and aerial imagery (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.).
* LiDAR and UAV datasets for benchmarking and validation purposes (OCM Partners, 2024; Philadelphia Lidar - LAS Files 2022 {2022} - Big Ten Academic Alliance Geoportal, 2022).
* Machine Learning Tools: Software libraries, Neural Network models for developing instance segmentation models, image processing (e.g., TensorFlow, PyTorch with Mask R-CNN).
* GIS Software: For spatial analysis and comparison with traditional data sources. (e.g., Quantum Geographic Information System (QGIS) (QGIS Development Team, 2021), Google Earth engine for data analysis and mapping).

**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 the effective planning and deployment of 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 a clear acknowledgment of its scope and limitations, setting a foundation for future advancements in digital twin technology and its applications in smart 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; Li et al., 2021). Moreover, these methods are limited 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 digital twin 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; Khan et al., 2022; Kuruvatti et al., 2022). Additionally, government initiatives aimed at sustainable urbanization and environmental stewardship emphasize the value of digital twins in informing data-driven decision-making processes (Angin et al., 2020; Chang et al., 2021; T. Deng et al., 2021; Mylonas et al., 2021).

In summary, digital twins significantly advance over traditional methods like LiDAR and UAVs in urban and city planning. They offer improved data integration, faster iterations, sustainability, and smart city applications. The development of digital twins, driven by AI and computer vision, is a response to the challenges and limitations of traditional methods, promising more efficient, cost-effective, and scalable solutions for urban planning and development.

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# Appendix A Annotated Bibliography

Chikhale, D., Munde, M., & Deosarkar, S. (2022). Atmospheric Effects and Behaviour of Electromagnetic Signals in the Millimeter Wave Range Wireless Communication. *International Journal of Microwave & Optical Technology*, *17*(2), 115–125.

The article provides valuable insights into the impact of foliage on the efficient deployment of millimeter-wave communication systems. Several references and studies are cited to underscore the significance of considering foliage effects in the design and deployment of millimeter-wave networks. Here are some key points discussed in the article are related to foliage and its impact on millimeter-wave deployment: (a) Atmospheric constituents, such as free space loss, rain attenuation loss, gaseous loss, foliage loss, humidity, cloud, fog, and penetration loss, significantly impact the propagation of electromagnetic signals in the millimeter wave range. (b) The presence of foliage is acknowledged as a significant factor causing attenuation in the millimeter wave range, particularly in non-line-of-sight communication scenarios. (c) The need for accurate measurements and analysis of foliage effects is emphasized to suggest new and improved models for designing and developing millimeter-wave communication systems. (d) Studies on foliage attenuation at specific frequencies, such as 35GHz, are referenced, indicating the importance of considering frequency-dependent foliage effects in millimeter-wave deployment. (e) The impact of foliage on signal attenuation in the millimeter band is highlighted, emphasizing the need for effective modeling and measurement of foliage effects to assess and mitigate signal losses accurately.

Overall, the authors underscore the critical role of foliage in the efficient deployment of millimeter-wave communication systems. It emphasizes the need for comprehensive understanding, measurement, and modeling of foliage effects to ensure the reliable and effective operation of millimeter-wave networks, especially in non-line-of-sight scenarios.

Farooq, U., & Lokam, A. (2023). Performance analysis of mmWave/sub-terahertz communication link for 5G and B5G mobile networks. *Frequenz*, *77*(11/12), 599–606. https://doi.org/10.1515/freq-2023-0024

The article provides a comprehensive overview of the evolution of mobile wireless communication to the 5G revolution, High-frequency communications, cellular communications, the architecture and emerging technologies of 5G networks, and a survey on millimeter-wave communications for fifth-generation wireless networks. Additionally, it discusses the potential of millimeter-wave (mmWave) and terahertz spectrum for 6G wireless with detailed references cited.

The article sets the stage for the subsequent analysis by establishing the context of the study within the broader landscape of wireless communication technologies, including the challenges and opportunities associated with the deployment of mmWave/sub-terahertz communication in 5G and B5G mobile networks.

Moreover, the authors underscore the intricate challenges entailed in the deployment of millimeter-wave communications, with a specific focus on the pronounced influence of foliage on the efficacy of mmWave/sub-terahertz communication. A critical aspect addressed is the substantial power loss encountered by mmWave/sub-terahertz signals as they traverse foliated environments. Delving into the nuances, the article introduces a robust mathematical model meticulously crafted to capture the essence of foliage-induced attenuation, thereby elucidating the gravity of its impact on communication links.

This foundational exploration serves as a precursor to the ensuing analysis, shedding light on the precise environmental variables that demand meticulous consideration for the seamless implementation of mmWave/sub-terahertz communication within the realm of 5G and beyond 5G (B5G) mobile networks. By delineating the mathematical intricacies of foliage loss, the article sets a compelling stage for a more detailed examination of the factors critical to optimizing the performance and reliability of mmWave and sub-terahertz communication in the evolving landscape of advanced mobile networks.

Anzum, R. (2021). Factors that affect LoRa Propagation in Foliage Medium. *Procedia Computer Science*, *194*, 149–155. https://doi.org/10.1016/j.procs.2021.10.068

The article emphasizes the impact on the factors that impact the performance of LongRange (LoRa) propagation in foliage medium. The authors highlight the importance of considering environmental factors such as temperature, foliage, and rainfall, as well as LoRa physical parameter settings and the Fresnel zone.

The authors highlight the limited existing research on LoRa propagation in foliage environments, noting that while the performance of LoRa in indoor and outdoor settings has been studied extensively, there needs to be more research specifically focused on foliage propagation. The article references previous studies that have demonstrated a decrease in range and channel quality for non-line of sight foliage propagation, as well as degradation in the Received Signal Strength Indicator (RSSI) with increasing distance between transmitter and receiver in foliage environments.

The article underscores the impact of foliage on LoRa network deployment. It sets the stage for the current study’s experimental analysis of LoRa propagation in a foliage medium, specifically a line of five date palm trees, and its potential contributions to understanding LoRa propagation channel modeling in foliage environments. The article highlights some of the challenges posed by foliage while deploying LoRa technology. (1) Signal Attenuation: Vegetation or foliage can cause significant signal attenuation, which can reduce the range and quality of LoRa propagation. This can be addressed by optimizing the physical layer parameters of LoRa, such as spreading factors, to improve signal strength and quality. (2) Multipath Propagation: Foliage or Vegetation can also introduce multipath propagation, which can cause interference and reduce the accuracy of signal reception. This can be addressed by using directional antennas or by optimizing the placement of LoRa gateways to minimize the impact of multipath propagation. (3). Environmental Factors: Environmental factors such as temperature, humidity, and rainfall can also impact LoRa propagation in vegetation. These factors can be addressed by carefully selecting the location of LoRa gateways and optimizing the physical layer parameters of LoRa to account for these environmental factors.

Overall, while there are challenges associated with using LoRa technology in the presence of foliage or vegetation, these challenges can be addressed through careful network planning and optimization. Being aware of the existence of foliage or vegetation within the deployment area and having a thorough understanding of it contribute to improved planning and optimization of LoRa. This awareness and comprehension make it feasible to attain reliable and high-quality LoRa propagation, especially in environments with foliage or vegetation.

Nguyen, H. X., Trestian, R., To, D., & Tatipamula, M. (2021). Digital Twin for 5G and beyond. *IEEE Communications Magazine*, *59*(2), 10–15. https://doi.org/10.1109/MCOM.001.2000343

Researchers face several challenges in developing 5G networks to their full potential. These challenges include the complexity of technology, infrastructure deployment, interference and spectrum management, standardization and compatibility, security and privacy concerns, energy efficiency, regulatory and policy challenges, and meeting the diverse requirements of various 5G use cases. Addressing these challenges requires collaborative efforts from researchers, industry stakeholders, and policymakers to ensure the successful development and deployment of 5G networks to their full potential.

The article highlights the potential of digital twin (DT) technology in facilitating the smart deployment of 5G and beyond. It emphasizes the integration of DT with the physical environment to visualize and predict the propagation of 5G radio signals, enabling accurate 3D modeling of urban terrains, buildings, and trees. This integration, along with advanced radio propagation models, allows for the accurate prediction of coverage areas for each base station across the city, which is crucial for successful 5G deployment. Furthermore, the DT enables continuous monitoring, testing, and near-real-time optimizations of the 5G network’s performance. It also supports continuous validation and optimization, relaxation of constraints at the initial stages of 5G services, and flexibility for new use cases. The article underscores the pivotal role of DT in addressing challenges and driving the successful deployment of 5G networks.

Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*, *6*, 3593. https://doi.org/10.1109/ACCESS.2018.2793265

The article delving into smart manufacturing and Industry 4.0 underscores the pivotal role played by digital twins and big data in the metamorphosis of traditional manufacturing processes into intelligent, data-driven systems. The authors accentuate the significance of the digital twin in achieving cyber-physical integration in manufacturing by constructing a virtual representation of physical assets and processes. This virtual model serves as a dynamic tool for real-time monitoring, analysis, and optimization of the physical system. The research revolves around the framework and characteristics of IT-driven service-oriented smart manufacturing, underscoring the necessity to address the diverse demands of all stakeholders involved in service collaboration.

In the realm of environmental monitoring systems, the article conducts a comprehensive review of existing systems, emphasizing the criticality of real-time data collection and analysis for smart manufacturing. Notably, the work underscores the pivotal role of digital twins in enabling cyber-physical integration and autonomous decision-making within smart manufacturing systems.

The article enumerates key benefits derived from the integration of digital twin technology. Firstly, the digital twin creates a virtual representation of physical assets and processes, amalgamating data from diverse sources, including sensors, IoT devices, and other data sources. Secondly, it facilitates real-time monitoring, allowing for the early detection of faults and anomalies. This is made possible by the virtual representation, tracking the behavior of physical assets and processes in real-time. Thirdly, the digital twin serves as a tool for optimizing the physical system by simulating various scenarios and predicting outcomes based on different decisions. Finally, it enables closed-loop control by providing real-time feedback to the physical system, allowing for efficient and effective processes.

In summary, the digital twin is instrumental in creating a virtual representation of physical assets and processes; it empowers real-time monitoring, analysis, and optimization, fostering closed-loop control for more efficient and effective processes.

Mazzacca, G., Grilli, E., Cirigliano, G. P., Remondino, F., & Campana, S. (2022). SEEING AMONG FOLIAGE WITH LIDAR AND MACHINE LEARNING: TOWARDS A TRANSFERABLE ARCHAEOLOGICAL PIPELINE. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVI-2-W1-2022*, 365–372. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-365-2022

The use of airborne laser scanning (ALS) and light detection and range (LiDAR) technologies has become a well-established practice for identifying and mapping archaeological evidence. LiDAR technology allows for the measurement and mapping of items or structures that would otherwise be hidden under vegetation. The ability to filter the returning signal created by the hit vegetation makes it an essential instrument in areas with dense forest or shrub cover. However, the generation of an accurate Digital Terrain Model (DTM) from LiDAR data relies on various factors, making the creation of a DTM a complex procedure that requires numerous assumptions and decisions during the project planning, data acquisition, and subsequent analytic workflow.

The proposed workflow involves a multi-level multi-resolution (MLMR) point cloud semantic segmentation, which uses machine learning algorithms to classify the 3D dataset into different categories, including vegetation and archaeological structures. The workflow is designed to filter out vegetation and detect hidden archaeological structures directly from LiDAR point clouds. The MLMR procedure involves the development of predictive models using a Random Forest algorithm with reduced manually annotated portions of the datasets, including known elements and discriminative features. The workflow also includes the generation of a bare-ground DTM and the use of visualization techniques for anomaly detection.

The use of machine learning algorithms in the proposed workflow provides a fast and accurate way to filter vegetation and detect archaeological evidence in LiDAR point clouds, facilitating the identification and mapping of archaeological elements above ground and anomalies of potential historical interest at ground level. The workflow is designed to be optimal, fast, and transferable, working in different archaeological environments to distinguish vegetated and non-vegetated areas in LiDAR datasets.

The proposed workflow demonstrates significant advantages in processing large LiDAR datasets, facilitating the otherwise difficult manual identification of hidden heritage evidence and saving time in the process execution. The workflow is designed to spot archaeological artifacts both above and below ground in multiple steps and work entirely on the LiDAR point cloud. It offers fast processing of large datasets through a supervised machine learning approach, accurate vegetation filtering in complex environments, and the detection and mapping of above-ground structures directly on the 3D point cloud. Additionally, the output is easily transferrable to a GIS environment for further data processing, and the classification models can be generalized and transferred to different environments.

Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities. *Sustainable Cities and Society*, *99*, 104862. https://doi.org/10.1016/j.scs.2023.104862

The article provides a comprehensive review focusing on Urban Digital Twins (UDTs) and their role in sustainable smart cities; a systematic analysis is presented, which outlines the primary challenges and unresolved issues in their implementation. The review underscores a significant research gap, noting that despite the uptick in UDT-related research, there remains an insufficient exploration of the bottlenecks hindering their deployment. The intention of this study is to bridge this gap through a meticulous examination of the associated challenges and issues. The analysis delineates eight principal categories of challenges that are pivotal to the realization of UDTs. These encompass concerns with interoperability and semantics, foundational infrastructure including storage, computation, and network systems, the intricacies of data acquisition and actuation, and the imperative of ensuring data quality and harmonization. Further, the need for robust modeling, simulation, and decision-support systems is recognized, alongside the criticality of data visualization and the display of information. The review also touches upon the necessity for adequate human and capital resources, and the importance of governance, as well as organizational and social considerations. The review draws particular attention to key issues such as the semantics of data and models, the prevalence of missing data, and the overarching need for data quality and effective modeling practices. These elements are identified as significant hurdles that practitioners must surmount to alleviate the delays in UDT implementation. A methodical approach underpins the review, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) methodology. This structured approach facilitated a targeted literature search and selection process aimed at unearthing relevant articles that address the myriad challenges encountered in the deployment of UDTs.

In summary, the literature review offers a thorough and insightful overview of the obstacles and unresolved matters surrounding the deployment of Urban Digital Twins in the context of sustainable smart cities. The findings provide a comprehensive resource for practitioners, policymakers, and scholars engaged in the domains of urban development and digital twin technologies, fostering a deeper understanding of the field and guiding future research and application efforts.

Sun, Z., Xue, B., Zhang, M., & Schindler, J. (2023). An Improved Mask R-CNN for Instance Segmentation of Tree Crowns in Aerial Imagery. 2023 38th International Conference on Image and Vision Computing New Zealand (IVCNZ), Image and Vision Computing New Zealand (IVCNZ). https://doi.org/10.1109/IVCNZ61134.2023.10343827

The article presents a new and effective method for segmenting individual tree crowns in aerial imagery, with a focus on the dataset of Wellington City of Aotearoa, New Zealand. The paper begins with an introduction to the importance of instance segmentation in computer vision and the challenges of segmenting individual tree crowns in aerial imagery. The authors then introduce the Mask R-CNN architecture and its limitations in extracting sufficient feature information for individual tree crowns.

To address these limitations, the authors propose an improved Mask R-CNN method by introducing an effective backbone structure, ConvNeXt, and a new mask branch to help segment tree crowns from complex backgrounds. The proposed method is evaluated on the Wellington city dataset, and the results show that it outperforms Mask R-CNN and accurately identifies and segments individual tree canopies.

The authors note that many of these methods are based on Mask R-CNN and that the performance of these methods is limited by the complex canopy structure of trees and the similarity of tree crowns to the surrounding background. The authors also discuss the potential real-world applications and implications of this improved instance segmentation method for tree crowns in aerial imagery, including forest management, urban planning, biodiversity modeling, and pest control.

Overall, “An Improved Mask R-CNN for Instance Segmentation of Tree Crowns in Aerial Imagery” presents a significant contribution to the field of computer vision and forestry management. The proposed method addresses the limitations of previous methods and provides a more accurate and efficient way to identify and segment individual tree crowns in aerial imagery. The paper also highlights the potential applications of this method in various fields, emphasizing the importance of accurate and efficient tree crown mapping for sustainable forest management and urban planning.

# Appendix B Topic Description and Supporting Literature

The “Digital Twin Representation of Foliage” research emerges at the intersection of advanced technologies and environmental understanding, aiming to create a nuanced digital replica of natural environments with a particular focus on foliage. As connected devices proliferate and 5G technology becomes pervasive, the project responds to the challenges presented by the deployment of millimeter-wave (mmW) networks, specifically addressing issues related to foliage impact on wireless signal propagation (Anzum, 2021; Chikhale et al., 2022; Farooq & Lokam, 2023). In this endeavor, the research delves into the intricacies of representing foliage within a digital twin, encompassing the spatial distribution, diversity, and inherent characteristics of trees and vegetation. These digital twin models serve as powerful tools, empowering network planners, environmental scientists, and various stakeholders to comprehend how foliage influences the complex dynamics of wireless signal propagation (Nguyen et al., 2021; Qi & Tao, 2018).

The "Digital Twin Representation of Foliage" research embarks on a groundbreaking journey, bridging the realms of technology and environmental comprehension to establish the groundwork for intelligent, efficient, and environmentally conscious network planning. With its focus on modern connectivity challenges, this research is positioned to make a significant contribution to the advancement of wireless communication technologies.

**Objectives**

* Foliage Modeling: Create a comprehensive digital twin of natural environments, emphasizing the spatial distribution and characteristics of foliage.
* Network Optimization: Provide network planners and environmental scientists with a robust tool for intelligent and efficient network planning, ultimately enhancing user coverage and throughput.
* Community Enrichment: Contribute to intelligent urban planning and environmental awareness by extending the digital twin to encompass additional elements like building facades and street infrastructure.
* Wireless Signal Dynamics: Uncover insights into how foliage influences wireless signal propagation, path loss, and coverage, especially in high-frequency networks like millimeter-wave (mmW) networks designed for technologies such as 5G.

**Outcomes**

* Accurate Foliage Representation: A sophisticated digital twin that precisely represents various foliage types, distributions, and characteristics.
* Enhanced Network Planning: Improved efficiency in the planning and deployment of 5G mmW networks, leading to superior coverage and reduced signal interference.
* Holistic Community Representation: Expansion of the digital twin to include additional urban elements, contributing to intelligent urban planning and enriched community experiences.