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Communications Mesh Test Deployment

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16. Abstract

The purpose of the Michigan Department of Transportation (MDOT) Unmanned Aircraft Systems (UAS) Communications Mesh Test Deployment project was to evaluate the feasibility of using short-range wireless mesh networks to support Beyond Visual Line of Sight (BVLOS) operations for UAS. The project focused on integrating Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) technologies, commonly used in connected vehicle systems, as a communications framework for real-time UAS command, control, and data transmission.

Methods included deploying and testing mesh network infrastructure at various locations in Michigan, including real-world BVLOS flight demonstrations conducted at a designated test site in Lansing. UAS, helicopters, and connected ground vehicles were used to evaluate communication availability, latency, network resilience, and multimodal coordination in urban and rural environments. Federal regulatory approvals were obtained to support operations. Results confirmed that DSRC and C-V2X technologies can effectively support BVLOS operations and enable multimodal integration with existing transportation infrastructure. However, communication performance was sensitive to terrain, vegetation, and building obstructions, emphasizing the need for careful placement of ground-based radio equipment. The study concludes that mesh-based communication systems are a viable and scalable solution for integrating UAS into intelligent transportation systems and recommends further research into three-dimensional UAS swarm testing, cooperative behavior modeling, and financial transaction capabilities.

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EXECUTIVE SUMMARY

Michigan has long served as a national leader in mobility and transportation innovation—from revolutionizing automotive manufacturing to advancing aerospace and air mobility technologies. Building on this legacy, the Michigan Department of Transportation (MDOT) conducted the Unmanned Aircraft Systems (UAS Communications Mesh Test Deployment project to evaluate whether a short-range wireless mesh network could reliably support Beyond Visual Line of Sight (BVLOS) operations for UAS. The project's objectives included assessing communication network performance, testing the integration of Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) technologies with UAS and ground vehicles, validating mesh network capabilities in various environmental conditions, and establishing a scalable communications framework for future Advanced Air Mobility (AAM) infrastructure. The project received required approvals and waivers from federal and state agencies, and real-world demonstrations involving UAS, helicopters, and ground vehicles were conducted at the Lansing MDOT State Offices and Logistics Facility. Testing also occurred in Detroit at Coleman A. Young International Airport.

Testing confirmed that using DSRC and C-V2X mesh-based communication networks can enable reliable communications for BVLOS UAS operations and support multimodal coordination with existing connected vehicle infrastructure. Real-time data transmission and Command, Control, Communicate, Compute, Cyber, Intelligence, Surveillance, Reconnaissance (C5ISR) functionality were successfully demonstrated, validating the core hypothesis of the project. However, the tests also revealed critical deployment considerations, most notably, that communication performance depends heavily on the strategic placement of roadside units (RSUs) due to radio signals' limited range and sensitivity to physical obstructions like terrain, vegetation, and buildings. These findings underscore the importance of environmental awareness and infrastructure optimization when planning for future UAS deployments. As transportation owner-operators increasingly deploy these communication systems for ground vehicles, the opportunity grows for shared use between air and surface modes, enhancing coordination, situational awareness, and safety across multimodal transportation networks.

Ultimately, the project demonstrates that integrating UAS into Michigan's intelligent transportation systems (ITS) using shared wireless communications infrastructure is both feasible and promising. The findings highlight a critical path forward for developing and deploying a unified, scalable mobility ecosystem that incorporates air and ground autonomous systems. Continued research is recommended to expand on these findings, particularly through three-dimensional UAS swarm testing and cooperative behavior modeling in dynamic environments. Moreover, the potential to extend the communication infrastructure's use to support future applications, such as financial transactions between vehicles and infrastructure, mirrors capabilities already used for tolling on express lanes nationwide. These next steps can help Michigan remain at the forefront of multimodal transportation innovation and continue to build the systems needed to manage the expected growth of autonomous vehicles and AAM operations expected to operate in the air and on the ground in the coming decades.

1. INTRODUCTION

1.1 Background

Michigan stands as a cornerstone of American industrial innovation, renowned for its pivotal role in both the automotive and aerospace sectors. Detroit, the heart of the automotive industry, pioneered mass production with Henry Ford's assembly line in 1913, making automobiles accessible, and establishing Michigan as home to industry giants like Ford, General Motors, and Chrysler (Ford Motor Company, n.d.). The state also led early road infrastructure advancements, notably constructing the nation's first mile of paved concrete road on Woodward Avenue in Detroit in 1909 (Coleman, 2023). Complementing its automotive dominance, Michigan's aerospace contributions, spanning over a century, highlight its versatility and industrial prowess.

In aerospace, Michigan's legacy began with trailblazers like the Detroit Aircraft Corporation, a 1920s holding company that advanced early aviation through manufacturing and innovation until its collapse in the Great Depression. The Stout Metal Airplane Company, founded by William B. Stout in 1922, marked another milestone. Acquired by Ford Motor Company in 1924, it produced the iconic Ford TriMotor, a three-engine aircraft that revolutionized commercial aviation with 199 units built between 1925 and 1933 (The Detroit News, 2014). Michigan further shaped aviation infrastructure by introducing the nation's first concrete-paved runway in 1928 at Ford Airport in Dearborn, enhancing safety and durability. Additionally, Detroit City Airport (DET, now Coleman A. Young Municipal Airport), opened in 1927, was among the earliest U.S. airports to feature a control tower in the late 1920s, a critical advancement in air traffic management.

During World War II, Michigan's industrial might shone with the 1941 construction of the Willow Run Bomber Plant in Ypsilanti. Operated by Ford, this 3.5-million-square-foot facility produced 8,685 B-24 Liberator bombers by 1945, playing a vital role in the Allied victory and earning the state its "Arsenal of Democracy" moniker. This dual legacy of automotive and aerospace innovation underscores Michigan's ability to lead across industries. From the assembly line to the TriMotor, paved runways to wartime production, the state's contributions have left an indelible mark on American history.

Michigan's automotive industry, a global leader in innovation, has invested billions to pioneer electric and hybrid-electric vehicles, as well as connected and automated vehicle (CAV) technologies. These advancements drive the development of clean, quiet, and intelligent transportation solutions, significantly reducing roadway accidents and fatalities, cutting carbon emissions, and alleviating traffic congestion, while reinforcing the state's legacy of transformative mobility.

MDOT has been a leading State Department of Transportation (DOT) in embracing Unmanned Aircraft System (UAS) and Advanced Air Mobility (AAM) technologies. Just as Michigan Department of Transportation (MDOT) has been a leader in advanced aviation technologies, MDOT is also future-thinking with connected ground vehicles and smart infrastructure, engaging research into pioneering technology such as Dedicated Short-Range Communications (DSRC) and similar next-generation technology such as Cooperative Vehicle-Infrastructure Systems (CVIS).

Unlike traditional radar technologies, which are often expensive to deploy and maintain, technologies such as DSRC and Cellular Vehicle-to-Everything (C-V2X) offer a more practical and cost-effective alternative. These systems are less costly and easier to maintain because they are built from widely available commercial off-the-shelf (COTS) wireless communication hardware. These technologies are being widely used for connecting ground vehicles and infrastructure and can be readily retrofitted for UAS systems, providing an opportunity for MDOT to leverage the technology as a foundation for exploring the integration of air vehicles, ground vehicles, and existing infrastructure, with the goal of developing a coordinated, multimodal transportation network that can enhance operational efficiency and improve safety.

1.1.1 Dedicated Short-Range Communication Technology

Dedicated Short-Range Communication (DSRC) technology has been instrumental in Michigan's efforts to enhance transportation safety and efficiency. DSRC is a wireless communication medium that enables vehicles to communicate with each other, such as Vehicle-to-Vehicle (V2V) and with infrastructure, or Vehicle-to-Infrastructure(V2I). This low-latency communication, operated in a dedicated spectrum in the 5.9 gigahertz (GHz) band, is crucial for applications like collision avoidance and traffic signal optimization. From 2005 to 2009, the United States Department of Transportation (USDOT) conducted a large-scale proof of concept project in Novi, Michigan (Andrews & Cops, 2009). In 2012, Michigan deployed approximately 2,800 vehicles and 25 roadside units equipped with DSRC as part of the Safety Pilot Model Deployment in Ann Arbor (Bezzina & Sayer, 2015). The data collected from this initiative informed updates to DSRC industry specifications, enhancing the technology's effectiveness in real-world scenarios.

1.1.2 Cellular Vehicle-to-Everything Technology

C-V2X technology represents the evolution of vehicular communication. Unlike DSRC, C-V2X leverages Long-Term Evolution (LTE) physical medium technology for use in the 5.9 GHz band to facilitate communication between vehicles, infrastructure, and even pedestrians. This technology offers extended range and enhanced capacity, supporting advanced applications like real-time traffic updates and coordinated vehicle platooning. In Michigan, research is ongoing to evaluate the reliability of C-V2X in various scenarios, including its potential to overcome limitations observed in DSRC systems.

Michigan's commitment to advancing transportation technology is evident through its historical contributions to aerospace manufacturing and current initiatives in AAM, DSRC, AVs, and C-V2X technologies. These efforts position the state as a leader in integrating innovative mobility solutions.

1.1.3 Automated Vehicles

AVs, commonly known as self-driving cars, use a combination of sensors, cameras, radar, and artificial intelligence to navigate roads without human intervention. These vehicles continuously process data to make real-time driving decisions. Michigan has been proactive in AV research and development. In August 2020, Governor Whitmer announced the development of a CAV corridor along a 39-mile segment of Interstate-94 between Ann Arbor and Detroit (Grinnell, 2020). This initiative aims to create a dedicated infrastructure for AVs, enhancing safety and efficiency in transportation.

In recent years, Michigan has continued leading in aerospace innovation, particularly with AAM. AAM aims to revolutionize transportation by integrating highly automated aircraft into the National Airspace System (NAS), facilitating the movement of people and cargo to areas underserved by traditional methods. AAM includes small UAS under 55 pounds to large automated vertical takeoff and landing aircraft and conventional takeoff and landing aircraft (CTOL). In 2020, Governor Gretchen Whitmer established the Office of Future Mobility and Electrification to further this vision (State of Michigan, 2020). By 2022, Michigan, in collaboration with Ontario, initiated a first-of-its-kind aerial mobility corridor study to test the feasibility of commercial drones and other aerial systems, including cross-border operations (Frezell, 2022).

As of April 2025, the Federal Aviation Administration (FAA) reports that more than one million UAVs have been registered, with more than 420,000 of these being commercial drone registrations (Federal Aviation Administration, 2025). Currently, there is no system to manage this new mobility platform. Market research from Stanford University suggests that more than 20 million ground autonomous vehicles will be in active use by 2030 (Stanford Online, 2020). Because all-new infrastructure is required to manage combined automated ground and aerial traffic, the FAA is continually updating regulations to provide for the safe integration of AAM operations into the NAS (Federal Aviation Administration, 2023).

1.2 Objectives and Scope

The MDOT UAS Communications Mesh Test Deployment project was conducted to evaluate the feasibility and effectiveness of using a Connected Intelligent Transportation Systems (C-ITS) Wireless Mesh Network to support BVLOS operations for UAS. The primary objectives accomplished as part of this project included the following.

Performance Assessment of a UAS Communications Mesh Network:

- Evaluated the stability, availability, and scalability of mesh communications for UAS operations.
- Analyzed data transmission availability and latency under various operational conditions expected when operating typical UAS use cases.

Tested the Integration of Short-Range Wireless Technologies for Air and Ground Vehicles:

- Explored the potential of C-V2X and DSRC technology for UAS operations.
- Determined the feasibility of integrating UAS communications with CAV infrastructure.

Evaluated C-ITS Architectures in Support of BVLOS and Multimodal Operations:

- Validated the ability of a communications mesh to facilitate flights in urban and rural environments.
- Tested and validated the potential of BVLOS operations during the UAS system testing.
- Confirmed DSRC architectures' capabilities for Command, Control, Communicate, Compute, Cyber, Intelligence, Surveillance, Reconnaissance (C5ISR) with the ability to transmit video over DSRC communications.
- Confirmed C-V2X architectures' capabilities for Command, Control, Communicate, Compute, Cyber (C5).
- Conducted real-world demonstrations involving UAS, helicopters, and surface-driven vehicles to evaluate the coordination, network efficiency, and overall integration of UAS with existing intelligent transportation systems (ITS).

Analyzed Network Resilience and Performance in Various Environmental Conditions:

- Conducted trials across different locations and conditions to determine the system's adaptability.
- Assessed potential interference sources and developed mitigation strategies to ensure reliable communications, such as orienting the antenna of communications devices installed on the UAS system to be oriented vertically during deployment testing.

Developed a Scalable Framework for Future AAM Network Deployments:

- Provided recommendations for implementing UAS communications infrastructure at the state level.
- Established guidelines for future research and expansion of aerial mobility corridors in Michigan.

Obtained Required Federal, State, and Local Approval:

- Obtained BVLOS and multiple UAS Demonstration Waivers from the FAA.
- Received airspace authorizations from the FAA and coordinated with local air traffic control (ATC) to operate within controlled airspace.
- Received Federal Communications Commission (FCC) experimental license for operations in the 5.9 GHz band.
- Obtained approvals from MDOT for regulatory compliance, site selection, and demonstration logistics.
- Provided necessary notification to Michigan State Police (MSP), MDOT ITS, and local agencies before the demonstrations.

1.3 Hypothesis

This study's hypothesis was that a short-range wireless mesh-based UAS communication network could provide a reliable, available, and scalable platform to support BVLOS operations. This network would enable real-time data transmission, effective coordination between airborne and surface-based assets, and seamless integration with existing ITS.

By testing this hypothesis through controlled experiments and real-world demonstrations, this project established a foundation for the future integration of UAS into Michigan's broader mobility infrastructure.

2. LITERATURE REVIEW

2.1 Review of Previous Research

Integrating UAS into the NAS and advancing connected vehicle technologies are pivotal in modernizing an aging transportation system. The project team conducted a literature review to examine key documents and studies that explore the development, testing, and deployment of UAS communication networks and connected vehicle infrastructures, with a focus on initiatives in Michigan. Results are provided below.

2.1.1 **Federal Agency Support of V2X Implementation**

A document published by the Intelligent Transportation Systems Joint Program Office of USDOT, *Saving Lives with Connectivity: A Plan to Accelerate Vehicle to Everything (V2X) Deployment*, presents USDOT's vision for the deployment of V2X as a coordination between the private sector and all levels of government (United States Department of Transportation, 2024). These efforts are intended to support a principal goal of the USDOT's National Roadway Safety Strategy, the reduction of roadway fatalities to zero, by deploying improved wireless connectivity technologies within the nationwide transportation system. This document outlines the phased goals and implementation plan of USDOT between 2024 and 2036 as part of the National V2X Deployment Plan, wherein deployment of V2X on National Highway System routes and at signalized intersections in major metropolitan areas progressively broadens, interoperability between deployments by public agencies is further tested, and nationwide use cases are further demonstrated.

USDOT aims to facilitate coordination across its constituent agencies to provide technical assistance, stakeholder engagement efforts, and professional capacity-building exercises to better support state agencies in V2X deployment activities. While the plan does not "imply a legislative/regulatory mandate or dedicated federal funding," it does establish funding direction prioritization within USDOT internally, recommending seed funding through discretionary grant programs, and to lower-level public agencies, recommending seed funding to enable interoperability testing through updated investment and transportation plans that integrate V2X.

2.1.2 **Standards for Communication in UAS Operations**

The FAA's UAS Traffic Management (UTM) Concept of Operations publication was first released in 2018 and then updated in 2020. In its most recent iteration, the publication establishes operational principles for low-altitude UAS operations under UTM and includes operational scenarios for BVLOS operations (Federal Aviation Administration, 2020). Distinct from traditional voice communication between crewed aircraft operators and ATC systems, the FAA anticipates UAS operators to communicate through a “distributed information network” that facilitates coordination between operators, the FAA, and other stakeholders without ATC services. Individual operators may elect to contribute toward this network through their own provisions or use third-party, government-approved UAS Service Suppliers that interface with the FAA through a Flight Information Management System .

The Radio Technical Commission for Aeronautics (RTCA), a not-for-profit, public-private partnership developing technical guidance for aviation authorities, developed Document 377B (DO-377B, *Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Uncrewed Aircraft Systems in U.S. Airspace*) to establish standards of communication between control stations and uncrewed aircraft (RTCA, Inc., 2023). These standards define necessary performance requirements to ensure reliable communication between UAS and their ground control stations, particularly for BVLOS operations.

DO-377B outlines the core need for low-latency, high-integrity data transmission to maintain continuous and reliable command links, specifying requirements for link availability, continuity, and redundancy to mitigate the risks of signal loss or degradation. Cybersecurity measures are also emphasized to protect UAS communication systems from interference or threats to access. The document emphasizes interoperability between UAS and other airspace users, including crewed aircraft and ATC systems. To this end, it establishes that Command and Control (C2) link technologies must be capable of integrating with existing aviation communication infrastructure, ground stations, and other cooperative air traffic systems. These standards provide a framework for UAS integration, ensuring that C2 operations meet the safety and performance benchmarks necessary for larger-scale deployment.

As UAS applications continue to expand into urban air mobility, cargo transport, and automated flight corridors, DO-377B performance standards will be an essential element in ensuring safety and regulatory compliance. DO-377B guidelines serve as a foundation for developments in UAS communications, bridging gaps between emerging aviation technologies and the regulatory frameworks required to support them. Ongoing research and deployment efforts, particularly those in Michigan, provide valuable insights into these innovations' practical challenges and potential solutions. Adherence to established performance standards, such as those outlined in DO-377B, and collaborative efforts among industry, government, and academia are pivotal in realizing the full potential of these technologies.

2.1.3 DSRC Application Deployment

In 2005, USDOT launched an initiative within its ITS Joint Program Office to enhance transportation safety through an ultimate vision of development and deployment of "nationwide wireless communication infrastructure that would allow communication between vehicles and between the vehicle and the roadside" (Resendes & Jones, 2005). A consortium between USDOT, American Association of Highway Transportation Officials, State DOTs, and light vehicle manufacturers was developed to research the feasibility of this technology and structure its implementation.

In 2008, this consortium engaged a Vehicle Infrastructure Integration proof-of-concept test in the northwest suburbs of Detroit, Michigan, to validate wireless communication standards in V2V and V2I applications, test core service applications, test concurrent use of applications, and demonstrate security protections against malicious network interference (Kandarpa, et al., 2009). The proof-of-concept test produced valuable findings on DSRC interoperability and robustness, test-bed deployment processes, and wireless access standards, among several other elements.

Success with core V2V and V2I functions was measured; however, communication strength from roadside equipment (RSE) to on-board equipment (OBE) degraded with distance, and prioritization issues were encountered when OBE entered the overlapping ranges of multiple RSE. These issues contributed to a recommendation for the further development of communications protocols. The test-bed deployment process evaluated the effectiveness of communications backhaul technologies, where it was found that Worldwide Interoperability for Microwave Access services offered proper stability and ease-of-use. However, these technologies were cost-prohibitive at the time. Though concerns with Society of Automotive Engineers (SAE) standards were observed during the testing process, test conductor developers worked with the SAE through the process to actively develop the standards and resolve these issues. The report recommended the specific development of other Institute of Electrical and Electronics Engineers standards to resolve these issues, namely with respect to overlapping RSE coverage areas.

Further supporting USDOT's priority to increase transportation safety, the University of Michigan Transportation Research Institute led a team of eight partners in conducting a Safety Pilot Model Deployment under the USDOT-run Connected Vehicle Safety Pilot program (Gay & Kniss, 2015). This deployment was undertaken in August 2012 in Ann Arbor, Michigan, using more than 2,800 connected ground-based vehicles at 29 sites. This process comprised four stages that collectively spanned four years: device development, pre-model deployment planning and testing, model deployment execution, and post-model deployment evaluation.

The particular objective of the deployment was to support the evaluation of DSRC technology in improving safety through V2V applications (Bezzina & Sayer, 2015). During the coordination phase of this project, large-scale data collection across multiple entities required careful organization and stakeholder and public outreach were also required because of the overall scale of the project. An interoperability test plan was submitted to USDOT to address DSRC device interoperability during pre-deployment testing. This plan supported a model deployment readiness initiative that assessed 125 items required to be confirmed as ready for launch prior to formal USDOT launch approval.

The deployment process included continued installation, deployment, and monitoring of V2V devices and RSE, as well as the extraction and processing of generated data. Data was collected and transferred intermittently to USDOT over a 12-month period.

Reporting on this process, Gay and Kniss (2015) detailed of a series of recommendations based on an analysis of project performance, including recommendations related to project management and performance measures, site selection, equipment selection, and data collection and transferal.

The National Aeronautics and Space Administration (NASA) published its *Testing Enabling Technologies for Safe UAS Urban Operations*, which is a NASA technical report from 2018 that details the validation and preliminary results of DSRC technology for CAVs. A summary of the key points related to DSRC results is provided below (Moore, 2021).

The study focuses on validating DSRC, a wireless communication technology designed for V2V and V2I communications, to support CAV operations. DSRC was evaluated for its potential to enhance vehicle safety, traffic efficiency, and autonomous driving capabilities through real-time data exchange. Tests were conducted at NASA's Kennedy Space Center using DSRC-equipped vehicles and infrastructure units. The experiments involved various scenarios, including intersection collision avoidance, platooning, and emergency vehicle priority, to assess DSRC performance in realistic CAV use cases.

Key findings related to DSRC reliability, range, and interoperability were reported. DSRC demonstrated low-latency communication (typically under 100 milliseconds), critical for safety applications like collision avoidance. The system maintained reliable data exchange even in dynamic environments with multiple vehicles. It also achieved effective communication ranges of up to 300 meters in line-of-sight conditions, though performance degraded in non-line-of-sight scenarios due to obstacles like buildings or foliage. The Packet Delivery Rate was high (above 90 percent) in most test cases, indicating robust data transmission. However, packet loss increased at longer ranges or in congested network conditions. DSRC units from different vendors showed good interoperability, successfully exchanging standardized messages (e.g., Basic Safety Messages) as per SAE J2735 standards. Additionally, tests in varied weather conditions (e.g., rain) showed minimal impact on DSRC performance, though further testing was recommended for extreme conditions.

This process tested applications in collision avoidance, platooning, and traffic management. DSRC enabled vehicles to share position, speed, and trajectory data, successfully preventing potential collisions at intersections. Vehicles maintained tight formations with consistent spacing, leveraging DSRC for real-time coordination. DSRC also supported priority signaling for emergency vehicles, reducing response times by adjusting traffic signals.

Testing also identified certain challenges. Signal interference from physical obstructions or other wireless systems (e.g., Wi-Fi) occasionally reduced performance. Scalability issues were noted in high-density scenarios, where network congestion led to increased latency or packet loss. Specific vehicle counts were not included in the report to contextualize the number of vehicles that led to network congestion and increased latency or packet loss. Additional research needs to be conducted to quantify what high-density entails. The need for widespread infrastructure deployment (e.g., roadside units) was also highlighted as a barrier to large-scale adoption.

DSRC showed strong potential for CAV applications, particularly in safety-critical scenarios, as a result of its low latency and reliability. Preliminary results supported its use in controlled environments like the Kennedy Space Center, but broader deployment requires addressing scalability and interference challenges. Future work includes testing DSRC in more complex urban environments, integrating it with 5G and other technologies, and conducting long-term reliability studies.

2.2 Summary of State-of-the-Art

C-V2X technology offers a promising avenue for enhancing vehicular communication, presenting a potential alternative or complement to traditional radar systems.

2.2.1 The Art of the Possible

C-V2X enables direct V2V and V2I communication, facilitating real-time data exchange that is critical for active safety applications. Operating in the 5.9 GHz band in the United States (Federal Communications Commission, 2024), C-V2X supports low-latency transmissions, making it suitable for time-sensitive interactions such as collision avoidance and traffic signal coordination. Its resilience to extreme weather conditions further underscores its reliability in diverse environments. DSRC offers similar capabilities and is available for use in other countries or in the 5 and 6 GHz Unlicensed National Information Infrastructure (U-NII) bands in the United States.

2.2.2 Importance and Potential Advantages Over Radar

While radar systems are proficient in detecting objects and measuring distances, C-V2X offers the added benefit of sharing detailed information between vehicles and infrastructure. This bidirectional communication allows for the dissemination of intent, status, and environmental data, enabling more informed decision-making. For instance, C-V2X can convey a vehicle's planned maneuvers or a traffic signal's phase timing, information that radar cannot provide. C-V2X can supplement radar by providing contextual data, leading to improved situational awareness and safety.

2.2.3 Efficiency and Affordability

- **Installation, Maintenance, and Repair:** C-V2X infrastructure typically involves the deployment of RSE and equipping vehicles with OBE. Compared to radar systems, which require precise calibration and regular maintenance, C-V2X systems are generally less complex and more cost-effective to install and maintain. Radar systems often entail significant operational costs, with annual expenses ranging from 5 to 10 percent of the initial purchase price, accumulating to match the hardware's cost over its lifespan.

- **Proven Technology with C-V2X Foundation**: C-V2X is built on established 3rd Generation Partnership Project (3GPP) LTE standards, ensuring interoperability and reliability. Extensive research and testing drove it development, leading to a mature technology with a solid foundation. This maturity translates to a lower risk of unforeseen issues and a smoother integration process into existing transportation systems.

- **Availability of Technology**: The components required for C-V2X implementation, such as transceivers and antennas, are readily available on the market. The technology has been standardized and adopted in various regions, facilitating easier procurement and deployment. This widespread availability also encourages competitive pricing, further reducing costs.

2.2.4 Limitations

While C-V2X offers numerous benefits, it is essential to acknowledge its limitations. The technology's effective range is typically up to 1,500 meters under optimal conditions, which may be insufficient in certain scenarios. Additionally, C-V2X operates in a specific frequency band that could be susceptible to interference from other devices. These factors necessitate careful planning and deployment strategies to ensure reliable performance.

3. METHODOLOGY

3.1 Experimental Design

The project followed a progressive, data-driven approach, building each phase on the findings of the previous stage. A combination of simulated environments, controlled experiments, and real-world deployments allowed for comprehensive validation of the UAS communications mesh. Collaboration with industry stakeholders, regulatory agencies, and academic institutions played a crucial role in validating the accuracy and applicability of the findings.

By systematically evaluating each communications network component, the project provided valuable insights into the feasibility, reliability, and scalability of integrating UAS into Michigan's ITS infrastructure. The results of this study can inform future policy and infrastructure investments, ensuring that Michigan remains at the forefront of AAM and connected vehicle integration.

3.2 Project Approach Summary

The approach to accomplishing the project objectives outlined above was structured around a phased, iterative testing model that allowed for the incremental development, deployment, and validation of the UAS communications mesh network. The strategy integrated multiple environments, regulatory coordination, and data analysis to test the system's viability for BVLOS operations and broader intelligent transportation applications.

The project team began by identifying key requirements for the communications network, including selecting DSRC and C-V2X technologies for real-time data exchange because the two technologies perform similarly. A layered testing approach was implemented, beginning with controlled simulations to refine communication protocols; this phase was followed by live flight testing in varied operational conditions.

To enable seamless regulatory integration, coordination with MDOT, FAA, and FCC played a pivotal role in the project's progression. The team worked closely with these agencies to secure testing waivers, define operational parameters, and establish compliance standards for UAS flight operations in controlled and uncontrolled airspace.

A key project element was the demonstration phase during which the system's ability to maintain stable communication across multiple aerial and surface platforms was tested. The deployment of roadside units (RSUs) and on-board units (OBUs) for the aircraft was structured to optimize network resilience by providing minimal latency and high-data integrity. Additionally, the project team conducted a robust GoldSET analysis to assess the regional scalability of technology and its potential for expansion across Michigan.

The GoldSET software, a WSP proprietary toolset, provided a robust flight area analysis by overlaying 21 geographic constraining factors, including population density, land use intensity, roadway traffic volume, physical obstructions, airspace boundaries, and institutional building locations. As demonstrated in Figures 1 through 4, providing visual examples of the results of this analysis, the flight operations area was selected for its physical distance from certain constraining factors and proximity to other regions that furthered the objectives of this project and simplified flight routing.

Generally, distance from residential areas and roadways provided the strongest constraints to narrow optimal siting, with population density and Annual Average Daily Traffic figures, respectively, constituting these measurements. Point layers describing the locations of MSP facilities, schools, hospitals, and detention centers also aided in constraining the site location. Other elements, namely roadway paralleling opportunities, railway paralleling opportunities, industrial and commercial land use, and bodies of water, were identified as beneficial in siting.

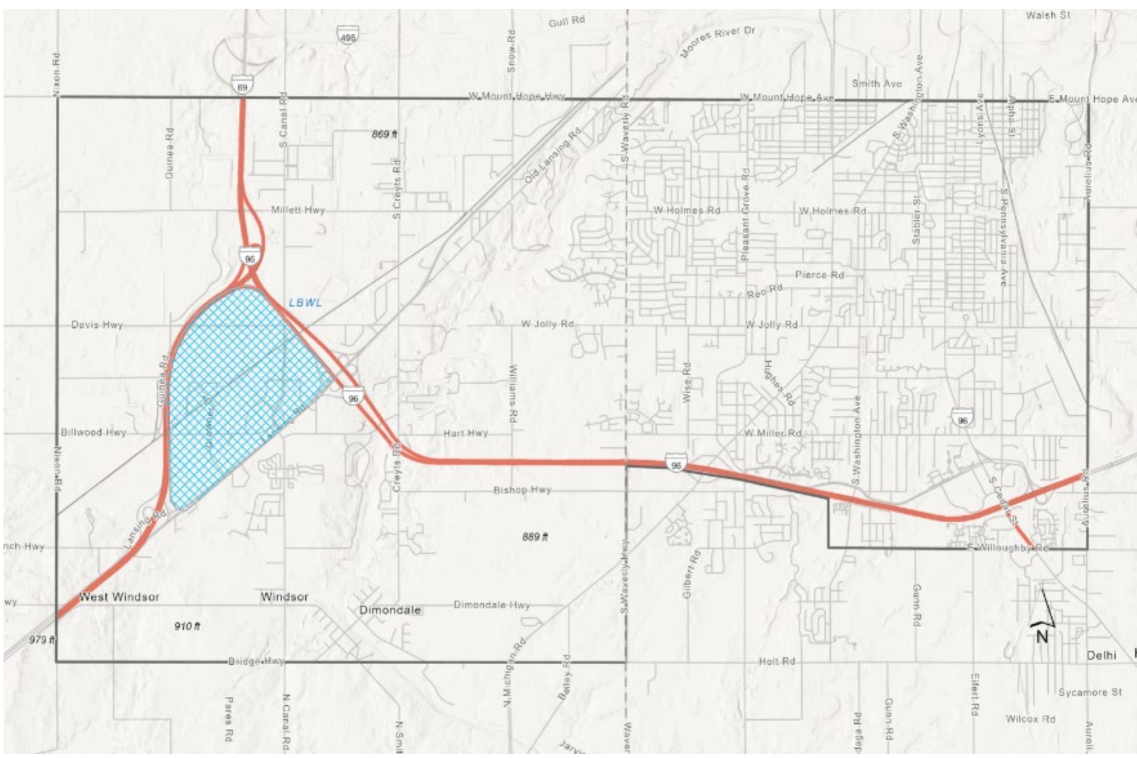


FIGURE 1. HIGH AVERAGE ANNUAL DAILY TRAFFIC COUNT - GOLDSET SITE ANALYSIS

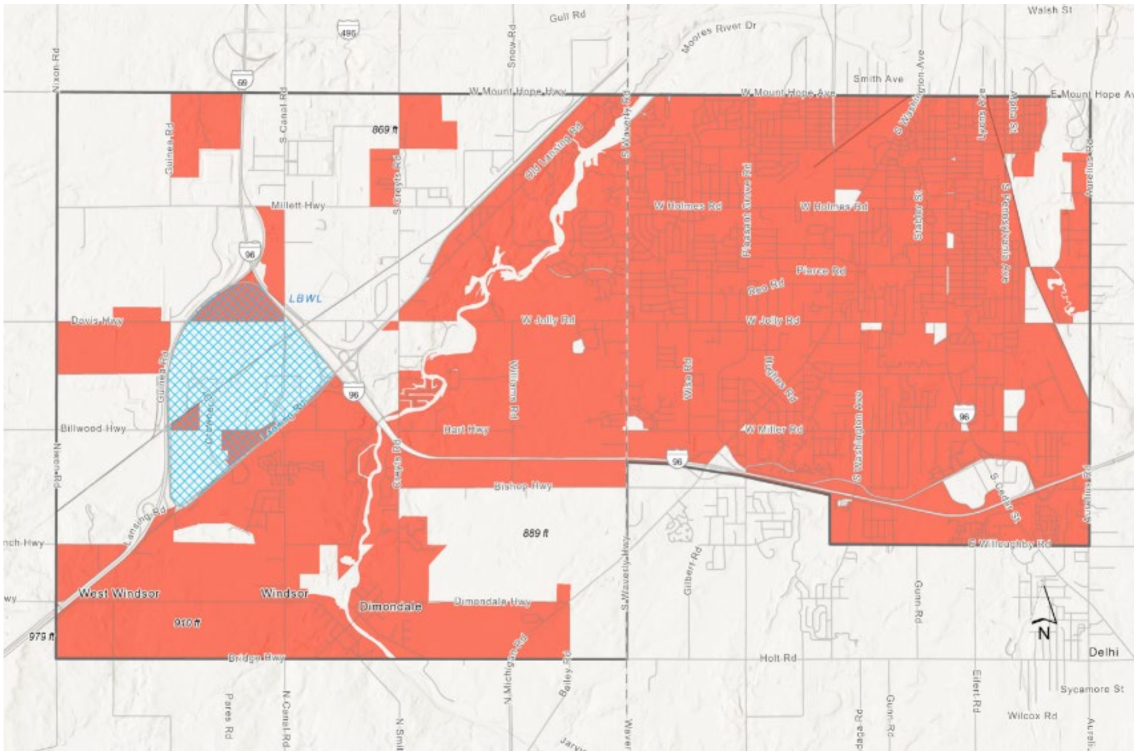


FIGURE 2. HIGH POPULATION DENSITY - GOLDSET SITE ANALYSIS

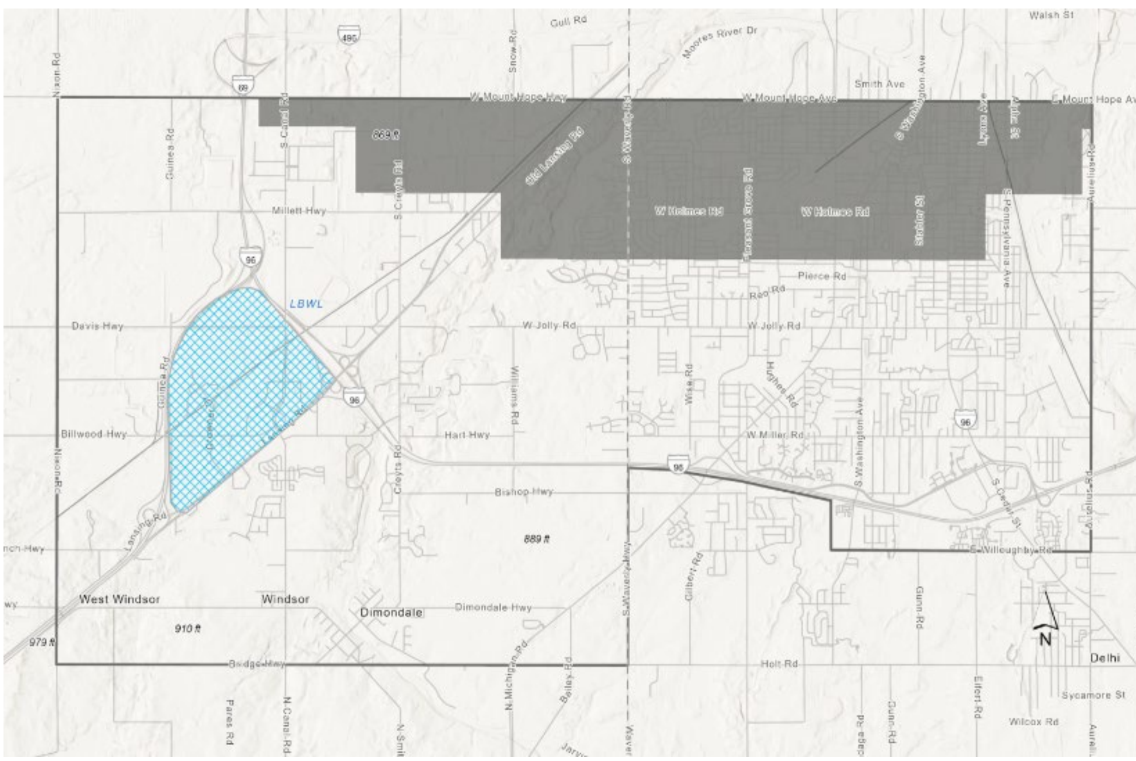


FIGURE 3. AIRSPACE EXCLUSION - GOLDSET SITE ANALYSIS

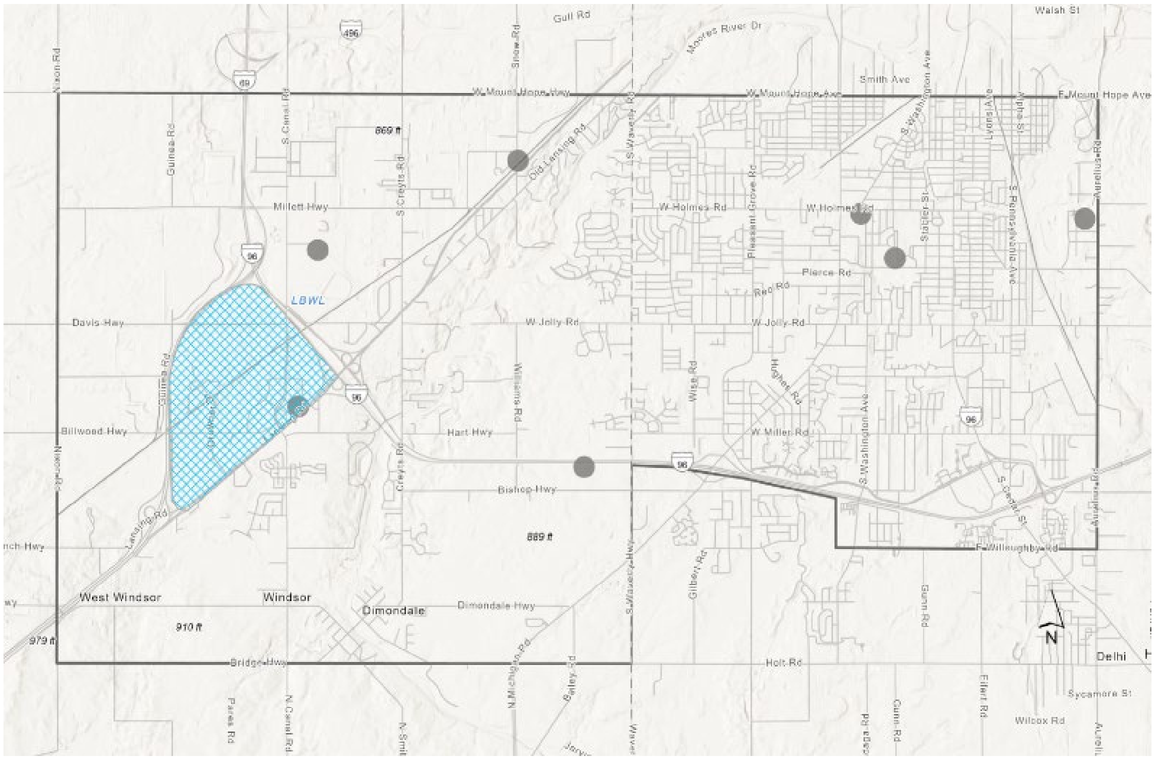


FIGURE 4. OBSTRUCTIONS OVER 300 FEET - GOLDSET SITE ANALYSIS

Two types of aerial platforms were used to meet the project objectives: (1) longer-range Unmanned Aerial Vehicle (UAVs) capable of time and distance flights BVLOS, and (2) shorter-range UAVs that could be operated as a coordinated swarm. The longer-range operations were used to confirm the operation of the communication mesh network needed to support BVLOS automated operations. The shorter-range UAV swarm was used to study the cooperative behavior of UAVs and to observe radio performance in a real-world environment where multimodal vehicles and physical obstructions (e.g., helicopters, surface vehicles, buildings, and trees) were present during the testing. Testing was conducted to evaluate the reliability of the communication mesh network and validate the feasibility of integrating UAS into real-world scenarios. Safe and efficient UAV routes were also identified to enable the rollout of UAS operations, either through an automated or manually controlled system, and to support a variety of UAS use cases. Performance metrics assessed the system performance and supported safe, reliable, and efficient UAS operations.

The project team synthesized the results from the demonstrations into a comprehensive assessment and evaluation of system performance, highlighting strengths and areas requiring further improvement. The demonstrations confirm the reliability of the UAS communications network and aircraft operations, including route planning. A next step would be to prepare for the future large-scale deployment of UAS communications networks and integrate UAS into real-world scenarios.

3.3 Demonstration Coordination

The demonstration phase of the MDOT UAS Communications Mesh Test Deployment was the project's culminating and critical milestone, requiring careful planning, regulatory approvals, and ongoing coordination among multiple stakeholders. The goal of this phase was to assess how well the communications mesh network could support BVLOS UAS operations in urban and rural environments.

3.3.1 Planning and Stakeholder Engagement

FAA and FCC approval were obtained for BVLOS operations and C-V2X communications compliance, enabling expanded operational testing.

URBAN TESTING – CONTROLLED AREA ADJACENT TO DET

Urban testing was conducted on October 17, 2024, in a part of the DET that had been decommissioned. This testing focused on signal propagation and coverage in an airport environment to identify the impacts of physical obstructions from surrounding buildings and trees. Testing the availability and reliability of communication provided insights into the adaptation of ground-based infrastructure, such as antennas and stations, to better support data transmission and reception and allow for scalable and cost-effective integration. Aircraft were also tested in a large operational area following various route assignments to help improve the planning of UAS operations and minimize the risk of real-world deployment. Once the testing was completed and validated, testing in an active area could be conducted.

RURAL TESTING –MDOT STATE OFFICES AND LOGISTICS FACILITY, LANSING

The testing for rural BVLOS operations was conducted on June 12, 2024; this testing was focused validating UAS capabilities and operations over longer distances. The testing was conducted in a more isolated environment to evaluate longer-range communication and network availability as well as system latency in a low-infrastructure area where interface obstruction from radio and terrain could occur. The testing offered insights into operational challenges and helped refine technical solutions for large-scale deployments. Key performance metrics such as signal strength, transmission rates, and system reliability were measured to assess UAS system performance, ensuring UAS operations met the required safety, reliability, and operational efficiency standards.

After the initial validation of network communications and aircraft flight operations, the next step was testing multimodal communication between UAS, helicopters, ground-based vehicles, and infrastructure (V2V and V2I). This involved testing UAS performing various maneuvers, peer-to-peer communications, and collision avoidance systems to confirm the feasibility of integrating UAS into real-world scenarios.

The project involved collaboration with multiple stakeholders, each playing a crucial role in the planning and regulatory approval process. MDOT, as the lead agency for this project, provided project oversight, funding, and logistical support. Eaton County Road Commission supported the UAS demonstration by providing access to rights-of-way for the placement of temporary ground stations. The FAA approved BVLOS operations and issued necessary flight authorizations for the project team. The FCC also approved the project's compliance with frequency spectrum regulations for C-V2X technology.

The project team focused efforts on a series of flight testing involving UAS, helicopters, ground-based vehicles, and infrastructures. Airspace Experience Technology (ASX) managed the system integration and communications technology implementation, while WSP USA contributed expertise in data analysis and led the post-testing reporting efforts. The project team partnered with Danlaw, which provided the C-V2X technology with devices such as RSUs and OBUs for the UAS system. The project team also worked and coordinated with local government agencies for surface rights-of-way, to obtain permits, and to ensure compliance with municipal regulations.

3.3.2 Michigan Department of Transportation Coordination

The MDOT UAS Communications Mesh Test Deployment relied on close coordination with MDOT for regulatory approvals, site selection, and testing and demonstration logistics. MDOT played a key role in securing necessary waivers, integrating UAS operations with state transportation infrastructure, and ensuring federal and state regulations compliance.

REGULATORY APPROVALS AND SITE SELECTION

MDOT's Office of Aeronautics and Research Administration worked with the project team to secure FAA BVLOS waivers and an FCC experimental license extension, coordinating with state ITS officials to prevent conflicts with existing systems. The office's input was also central to selecting the Lansing MDOT State Offices and Logistics Facility (Lansing MDOT facilities) as the primary test site. This decision followed a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of multiple locations, with MDOT providing key insights on property access, infrastructure, and airspace considerations.

DEMONSTRATION SUPPORT AND LOGISTICS

MDOT also assisted with site access, infrastructure placement, and installation logistics for ground station equipment. It worked with the project team to finalize test flight scenarios and informed MSP, MDOT ITS, and local agencies ahead of demonstrations to streamline flight operations and prevent disruptions.

INTEGRATION WITH MICHIGAN'S TRANSPORTATION NETWORK

MDOT collaborated with the project team to assess how UAS communications mesh technology could integrate into Michigan's ITS. Discussions focused on UAS-to-vehicle connectivity, traffic monitoring, and emergency response applications all of which could support future policy considerations for the state's AAM operations.

FEDERAL COMMUNICATIONS COMMISSION WAIVERS

FCC waivers were a critical component of the numerous tests and demonstrations, allowing the project to operate legally within designated frequency bands for UAS-to-ground and UAS-to-UAS communication. In collaboration with MDOT's Office of Aeronautics and ITS Division, the project team navigated the waiver process to obtain the necessary approvals for testing and demonstrations.

EXPERIMENTAL LICENSE AND SPECTRUM AUTHORIZATION

To support the deployment of DSRC and C-V2X technologies, the project team applied for and received an FCC experimental license for operations in the 5.9 GHz bands. The initial license permitted operations within a 20-kilometer (km) radius of the project team's Illinois office and a 50-km radius around DET. However, as testing expanded, a modification request was submitted to extend the coverage area to include the Lansing MDOT facilities site.

MDOT's ITS division concurred with the expanded license and indicated that it did not interfere with state-managed transportation systems. The FCC required confirmation from public safety license holders, in this case, MDOT, to mitigate potential frequency conflicts.

IMPLEMENTATION AND COMPLIANCE

Once the FCC waivers were approved, the project team installed and tested RSUs and airborne communication systems at DET and the Lansing MDOT facilities site. Initial trials assessed signal strength, interference risks, and handoff efficiency between nodes. The results from these tests informed adjustments to system configurations to optimize performance while maintaining FCC compliance parameters.

FEDERAL AVIATION ADMINISTRATION WAIVERS

The deployment required FAA waivers to conduct BVLOS operations and multi-aircraft testing and demonstrations at DET and the Lansing MDOT facilities site. These waivers were essential to ensure that test flights complied with federal aviation regulations and could be conducted safely in controlled airspace.

The project team applied for two separate FAA BVLOS waivers. The first waiver was for the Sentaero 5 UAS BVLOS waiver, which was approved for operations at both DET and the Lansing MDOT facilities site. The second waiver was for the Freefly Systems BVLOS waiver, which was submitted and approved for operations at the Lansing site.

The Sentaero 5 waiver allowed ASX to conduct BVLOS test flights with the longer range and duration available from a fixed-wing UAS platform. The Freefly Systems waiver allowed the team to conduct slower, precision BVLOS test flights with a quadcopter-style UAS.

In addition to the BVLOS waivers, the project required airspace authorizations and need to coordinate with local ATC to operate within the controlled Class D airspace at DET. FAA approvals ensured that all UAS operations were integrated with existing manned aircraft traffic, and that appropriate safety measures were in place.

To support large-scale testing, the project team also applied for a waiver to operate multiple UAS under a single remote pilot, allowing up to 30 aircraft to fly simultaneously. This waiver was valuable for evaluating the scalability of the communications mesh and its ability to support high-density UAS traffic.

To obtain the waivers, the project team submitted detailed risk assessments and flight safety plans for evaluation, established geo-fenced flight corridors for safe UAS operations, and mitigated airspace conflicts by implementing detect-and-avoid protocols.

3.3.3 Demonstration Execution and Testing Conditions

URBAN TESTING – DET

The DET airport testing evaluated UAS communication performance in congested airspace and urban settings where interference and network congestion are more likely to affect performance. UAS operations were conducted within a 5-square-mile test zone, and RSUs were strategically placed at the north end of the airfield near Conner Street, on the west side of the airfield near the freight circle, and on the roof of the main terminal building, enabling coverage of the entire active area of the airport (Figure 5).

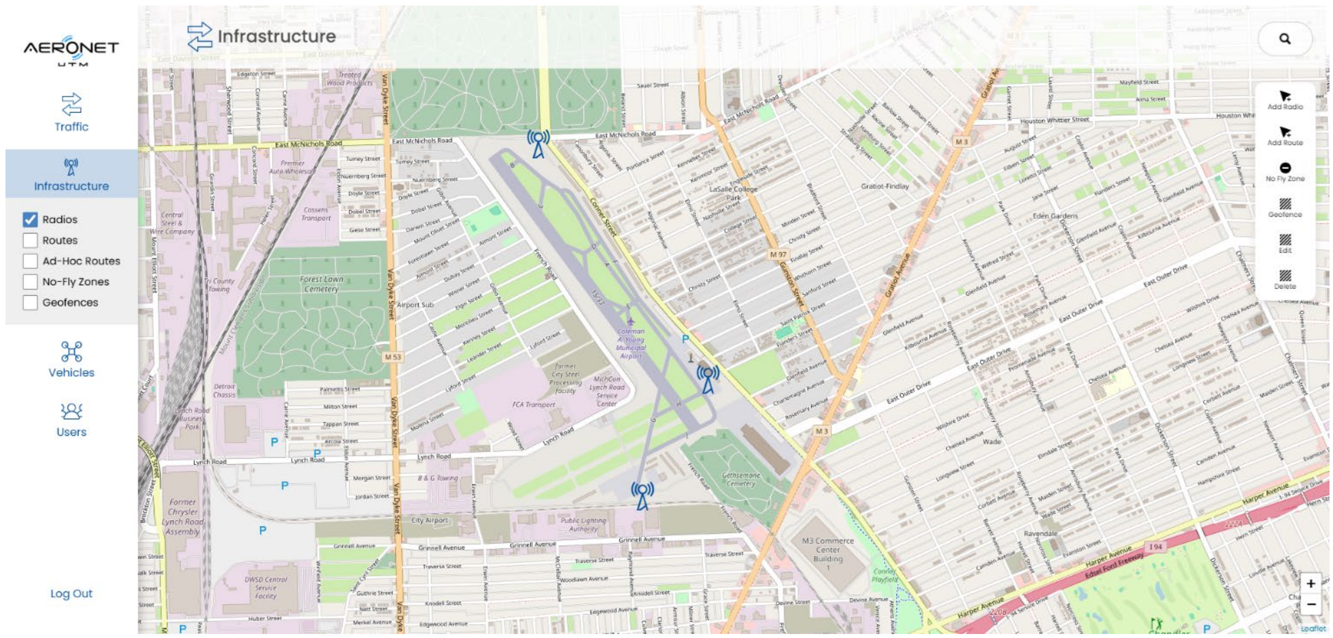


FIGURE 5. LOCATION OF RSUS AT DET - C-V2X AT THE NORTH AND WEST, DSRC AT THE EAST

UAS system performance testing included communication network latency and availability analysis under dense infrastructure conditions with typical line-of-sight obstructions. The network's availability was tested as the UAV moved between different communication nodes. Multimodal integration and interoperability between UAS, connected ground vehicles, connected air vehicles, and infrastructure were also conducted to assess UAS system safety, communications network reliability, and efficiency.

RURAL DEMONSTRATION –MDOT STATE OFFICES AND LOGISTICS FACILITY, LANSING SITE

The Lansing MDOT facilities site demonstration provided insight into how the UAS communications mesh would function in a low-infrastructure, open-air environment with fewer obstructions but greater distances between communication nodes. The test flights covered a 2-mile radius, assessing longer-range network availability at a test site that included highway corridors, office and industrial buildings, and open farmland, mimicking conditions found in many rural parts of Michigan.

Key evaluation metrics included communication network availability over extended distances, the effectiveness of C-V2X in low-traffic conditions, and the effect of terrain and vegetation on communication reliability.

SAFETY AND OPERATIONAL OVERSIGHT

Given the complexity of BVLOS operations, the demonstrations adhered to strict safety and operational protocols, including pre-flight system validation to check that all communications nodes were fully operational before each test flight. Redundant communication pathways were also implemented as fail-safe measures in case of signal degradation or network dropouts. Furthermore, FAA-certified remote pilots were on-site during the testing to oversee all flights and ensure compliance with regulatory requirements. Emergency response teams were also stationed on-site and ready to intervene in the event of an unexpected system failure or airspace conflict.

DATA COLLECTION AND PERFORMANCE METRICS

Throughout the demonstration phase, real-time data were collected and analyzed to assess the communications mesh's performance. Key data collection points included availability metrics for C-V2X, packet loss analysis to identify communication dropouts, and the completeness of the opportunity to communicate between aircraft and ground infrastructure. Multimodal coordination performance was also collected to evaluate how well the system integrated UAS and ground vehicles.

The collected data validated the feasibility of scaling the mesh network for statewide deployment, indicating that both urban and rural environments could support reliable UAS communication infrastructure.

IMPLEMENTATION AND SAFETY MEASURES

Once the Freefly Systems BVLOS waiver was approved, initial test flights were conducted at DET to assess signal stability, latency, and communication handoffs between airborne and ground-based assets. Additional safety protocols developed and adopted included pre-flight system checks to validate equipment and communication links, real-time monitoring from the command center for network stability, and emergency response planning in coordination with the MSP and local ATC.

As FAA approvals progressed, test operations expanded to the MDOT Lansing facilities site, where additional system validation flights were planned to further assess the network's performance in a different environment.

3.3.4 Equipment

OBUs mounted on vehicles and RSUs spaced around the operating environment were the primary pieces of equipment . Radios come in both C-V2X and DSRC varieties, and ASX tested both in the lead-up to the final demonstration. OBUs had to be modified and tested to find optimal configurations to suit a variety of vehicle configurations, and RSUs had to be built into portable stands to reflect how permanent installations would work.

C-V2X and DSRC are related technologies that both show promise for real-world connected vehicle applications, so ASX tested both during this project. C-V2X has the advantage of being a new technology with more resilience to interference, but DSRC offer some extra features and has higher adoption at this point. ASX ultimately found a setup that worked for both technologies, so the final demonstration included both styles of radio.

During testing, the project used Censys Sentaero 5, AG3, Flythru, and FreeFly Astro drones, supported in the air by a Robinson R44 helicopter and on the ground by two vehicles. With the variety of vehicle types included in the final demonstration, the OBUs had to be modified to suit different use cases. ASX created custom cases for OBUs to lower their weight and securely mount them to the different vehicles. Each vehicle platform offered a different power standard that had to be adapted to support the OBUs.

A variety of antenna styles and installations were tested to find the setup that provided the best range, availability, and latency. It was important to conduct reception tests to determine which antenna performed the best. The antennas needed to have superior reception, a lightweight design, and secure adjustment. Several antenna styles were tested before ASX found some mini antennas that met all requirements.

While enough C-V2X RSUs were available for the project, only a single proper DSRC was available, and more had to be fabricated. To create enough DSRC RSUs, ASX adapted some OBUs into RSUs to cover the full operating area of the final demonstration. This task required selecting connectors, building an enclosure, and adjusting the software to achieve the same performance as the off-the-shelf RSU.

Initial testing at DET informed ASX's equipment decisions for the final demonstration. The airport is an ideal testing ground because it includes a wide area with a mix of open and obstructed lines of sight. This environment also provided convenient opportunities to test at higher elevations using helicopters stationed at the airport. Based on airport testing, ASX was able to understand the performance capabilities of both C-V2X and DSRC.

One key takeaway from testing at DET was the impact of line-of-sight obstructions on DSRC performance. Certain physical obstructions, such as the ATC tower, nearly completely blocked DSRC OBU transmissions from reaching RSUs, while the same obstruction did not affect the C-V2X OBUs as much. This difference highlighted the importance of properly siting the RSUs for the final demonstration—RSUs needed to be sited such that there are minimal physical obstructions to affect system availability and that there are enough RSUs to overcome unavoidable obstructions.

Another interesting finding from testing at DET was related to the accuracy of OBU location tracking. Airport runways are nearly completely flat. As a result, they serve as an excellent area to test location and elevation accuracy. Ground vehicle testing on the runway revealed that longitudinal and latitudinal OBU positioning is very accurate, but elevation tracking is much less precise. On the completely flat runway, elevation could fluctuate as much as 10 meters up or down. This fluctuation is due to the history of the Global Positioning System (GPS) putting a lower significance on vertical tracking accuracy. Using connected vehicle technology in air vehicles will require additional sensors to compensate for the inaccuracy of GPS elevation.

Multiple tests were conducted at the Lansing MDOT facilities site prior to the final demonstration, and those tests revealed the importance of deploying an RSU at the launch/land site. Because there are more physical obstructions on the ground than in the air, it stands to reason that these connected vehicle technologies would have trouble on the ground far away from an RSU. In an urban environment, it is highly likely there will be buildings, vehicles, foliage, or something obstructing the line of sight, unless there is an RSU located at the launch and landing site.

4. PROJECT EXECUTION

The project team executed the project following the outlined methodology. The project unfolded in multiple phases, beginning with planning and coordination, where test site locations were finalized, regulatory approvals were secured, and all necessary equipment was configured. Initial testing flights were conducted to establish baseline performance and calibrate communication nodes.

Following preliminary assessments, full-scale demonstrations were executed with multiple UAS operating in BVLOS scenarios. These trials helped evaluate the stability of mesh communication, particularly when coordinating between airborne and surface-based assets. After the final demonstration and data collection phase, the project team identified key performance trends and assessed the feasibility of scaling the network for future applications.

This structured approach provided a comprehensive UAS communications mesh network evaluation, offering valuable insights into its operational potential and informing future research and deployment strategies.

4.1.1 Demonstration Coordination and Approvals

The project methodology's initial steps were dedicated to the larger demonstration coordination efforts and approval applications needed to achieve project goals. The project team coordinated with the FCC to conduct various wireless communications tests. The team applied for and successfully obtained an FCC experimental license to operate C-V2X devices over the air. Coordination with the FAA was necessary to receive BVLOS and multi-UAS waivers.

The project team coordinated with numerous equipment providers to build the UAS and include communications components to be tested. In each instance, equipment was inspected for damage and tested for overall functionality before being accepted.

Ongoing communication and coordination with MDOT were necessary to finalize the scope and details of the demonstration based on the on-site location. Upon finalizing the site demonstration location, the project team obtained final approval from MDOT of the operating scenario for the UAS communications mesh demonstration.

4.1.2 Demonstration Site Exploration

The project team conducted a detailed SWOT analysis and followed a site selection methodology to determine the optimal site for conducting UAS operations.

Each site was reviewed using multiple tools and methodologies. Google Earth was used to measure distances and assess the overall context of each site. Geographic Information System (GIS) data were evaluated by the GoldSET software to discern obstacles, hazards, population density, traffic conditions, and various other factors. All strengths and weaknesses were measured. Finally, the project team visited each site to personally observe conditions, measure radio frequencies, and identify any unseen obstructions.

4.1.3 Equipment Build and Testing

This project required ground-based equipment to support both the connected vehicle network and final demonstration. The ground side of the network consisted of five RSU radios to optimize system availability; those RSUs were mounted in a manner consistent with how they would be permanently installed on public roads. The final demonstration required audio and video equipment to present information and live feeds to attendees and system monitoring equipment for the project team.

For this project, ASX built and installed five portable RSU stands, shown in Figure 6, around the Lansing MDOT facilities site. Four stands were sited at the corners of the area, and one was installed at the command station where UAVs launched and landed. Each portable RSU stand included the following:

- One C-V2X RSU
- One DSRC RSU
- One Power Over Ethernet (POE) Switch
- One Cradlepoint Cellular Router
- Three Ethernet Cables
- One Power Bank
- One 15-Foot Mounting Pole
- One Base Stand
- One Base Plate

FIGURE 6. C-V2X AND DSRC RSU ON TEMPORARY POLE

Both RSUs were mounted atop the 15-foot mounting pole that was placed inside the base stand. Each RSU received power from the POE switch through an Ethernet cable. The Cradlepoint provided secure network access to the RSUs through a virtual private network (VPN)-secured backhaul and connected to the switch with an Ethernet cable. Both the POE switch and the Cradlepoint were powered by the power bank and safely installed inside of the base stand. Finally, the base stand was anchored to the base plate and secured by two sandbags. This setup provided a realistic representation of how connected vehicle technology would be installed in a permanent roadway installation.

At the command station (Figure 7), ASX set up a stage to show attendees the connected vehicle system. This stage consisted of the following:

- One Mounting Truss
- Three Outdoor Televisions
- Three Computers
- Two Speakers
- Two Microphones
- One Portable RSU Setup
- Four Sandbags

FIGURE 7. PRESENTERS AND VIDEO DISPLAYS AT THE DEMONSTRATION

The mounting truss served as the stage's centerpiece where the presenters stood and attendees watched. Three TVs mounted on the truss displayed the presentation from one computer and live video feeds from the other two. Both speakers were placed at the sides of the truss to project the presenters' voices to the audience, and the whole truss was weighed down with sandbags. In addition to the presentation equipment, the truss was used to mount a set of RSU equipment from the portable stands to service the launch and landing site.

Equipment used by the project team to monitor the connected vehicle network was also at the command station. Data from each portable RSU stand was aggregated back to the central hub running from the command station. This hub setup included:

- One Cradlepoint
- One Raspberry Pi
- One (each) Monitor, Keyboard, and Mouse

A Raspberry Pi served as the central hub device, aggregating vehicle data from across the system. The Cradlepoint was used to create a secure VPN network connecting the portable RSU stands to the Raspberry Pi. The ASX team monitored the Raspberry Pi to ensure the live feed worked and received vehicle messages during the entire operation. The AeroNet UTM traffic map, as shown in Figure 8 was displayed on the monitor to show real-time updates from the vehicles for the team to monitor and share with attendees.

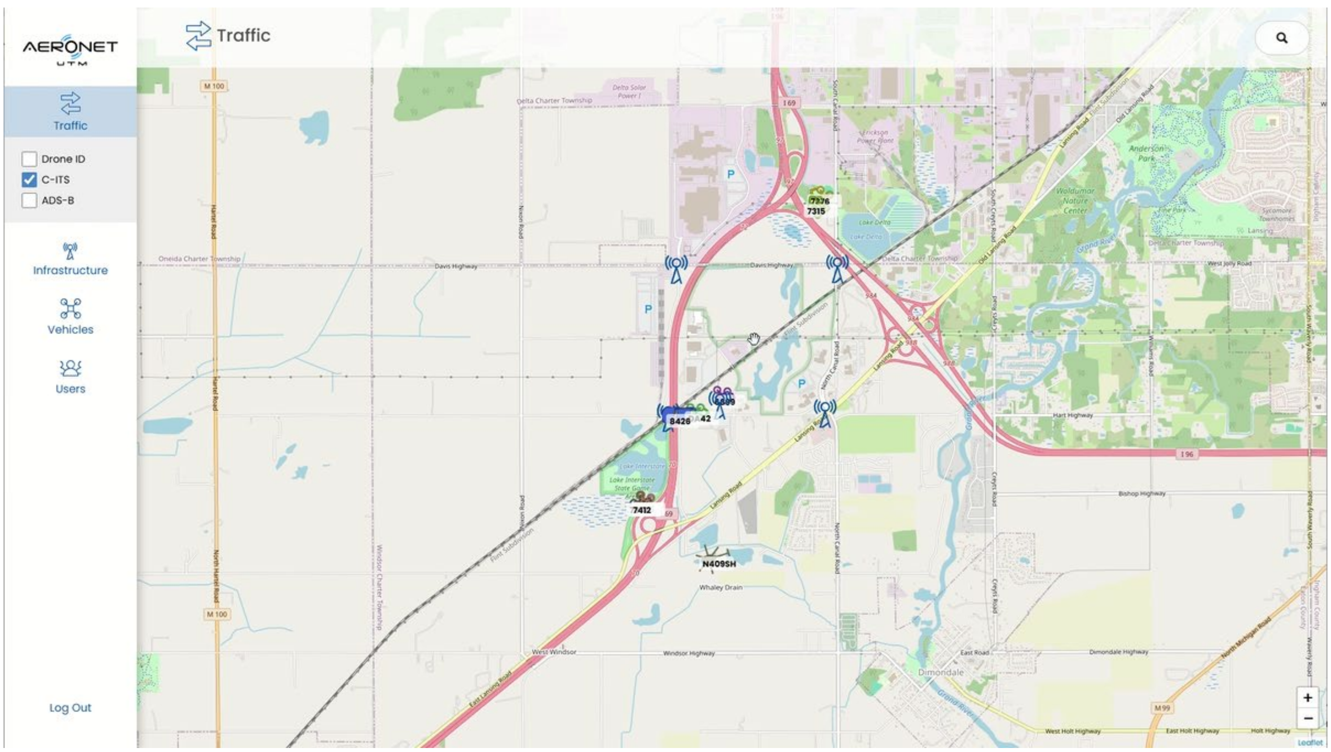


FIGURE 8. AERONET UTM MONITOR STATION DISPLAY - RSU AND VEHICLE LOCATIONS

4.1.4 Trial and Demonstration

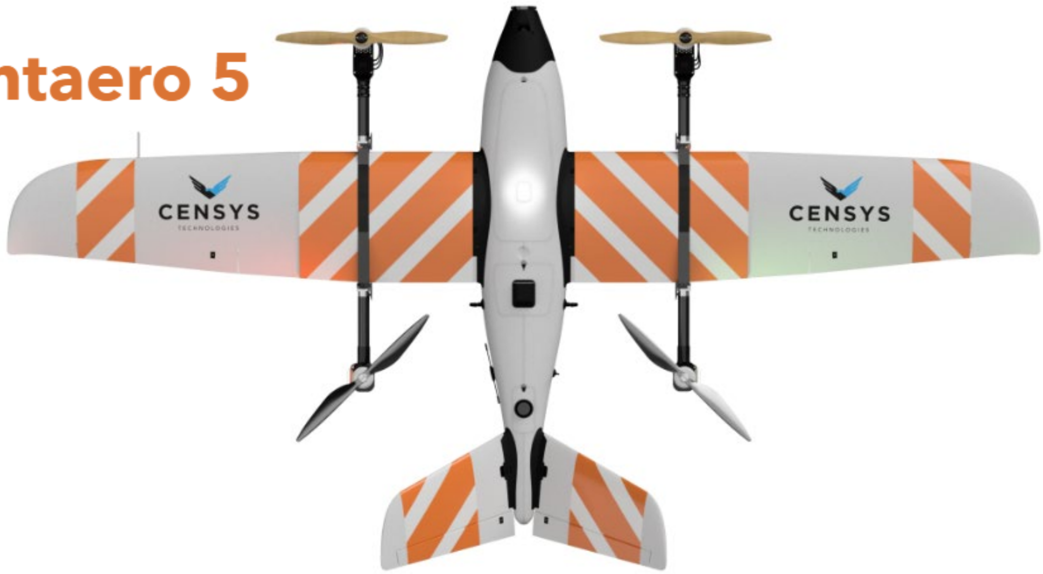
UAS AIRCRAFT SELECTION

Various UAS aircraft were evaluated as candidates for the BVLOS trials and multimodal communication demonstration, with the selection process focusing on factors such as the requirements for flight precision and duration for various typical use case scenarios. After a thorough assessment, two aircraft were ultimately chosen for the demonstration: the FreeFly Astro and the Sentaero 5, a two-phase lift + cruise aircraft manufactured by Censys. Figures 9 and 10 provide a reference image of the aircraft.

Both aircraft were equipped with OBUs and communication equipment optimized for maximum signal strength, which was necessary for data collection during the BVLOS trial and demonstration to record the effects of radio interference and terrain obstructions on the UAS system and communication performance.

FIGURE 9. FREEFLY ASTRO UAS PLATFORM USED IN THE DEMONSTRATION

Sentaero 5



1 hr	40 mi	25 mph	25 lbs
Endurance	Range	Max Wind	MTOW

FIGURE 10. CENSYS SENTAERO 5 UAS PLATFORM USED IN THE DEMONSTRATION

SURROGATE AIRCRAFT/MULTIMODAL COMMUNICATIONS DEMONSTRATION

On November 26, 2024, a field test was carried out at the Lansing MDOT facilities site, with the command center and UAS operations staged at the Horatio S. Earle Learning Center. The demonstration was structured to test the multimodal communication systems using three distinct vehicle/mode types: a helicopter, a surface vehicle, and a small UAS. The demonstration aimed to integrate these various systems in a controlled environment, emphasizing safety and data collection to assess the feasibility of integrating these systems and technologies into real-world applications.

As shown in Figure 11, the demonstration used five strategically placed temporary RSU communications towers, depicted as blue dots in the figure, to support command center communications. The towers were located at the following sites:

- Davis Highway and Guinea Road
- Davis Highway and Canal Road
- Canal Road and Lansing Road
- Davis Highway and Guinea Road
- Davis Highway and Canal Road
- Canal Road and Lansing Road

The red highlighted area in Figure 11represents the flight boundary for helicopter operation, while the green highlighted area represents the flight area specific to UAS. The testing was conducted under predefined safety measures, such as providing a vertical and lateral separation between the UAS and helicopters through pre-planned flight patterns to avoid conflict and maintain clear communication between ground and aerial teams.

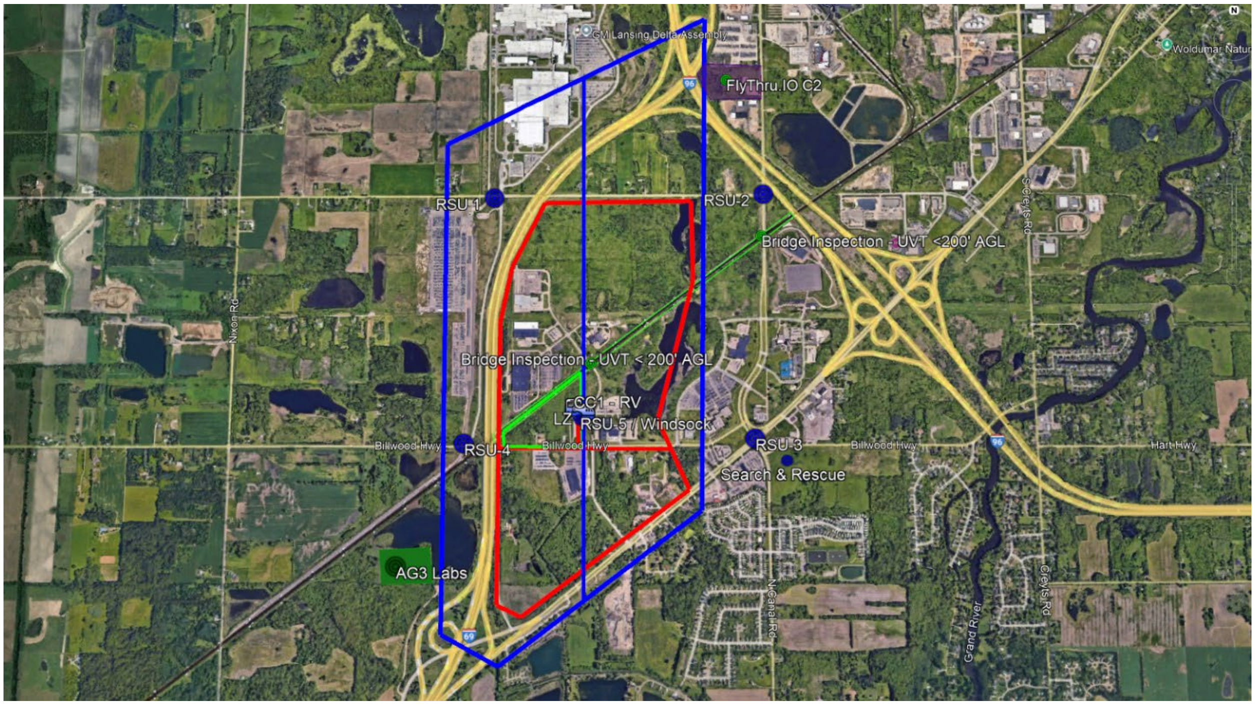


FIGURE 11. ROUTE PLANS FOR LANSING DEMONSTRATION OPERATIONS

The demonstration marked a critical milestone in advancing the integration of UAS with existing infrastructure. Communication capabilities were successfully demonstrated across the entire BVLOS circuit despite limitations on UAS operations from high winds during the demonstration. The following chapters discuss the results of the demonstration.

5. FINDINGS

5.1 Summary of Data

This section presents the data analysis and highlights key performance metrics from the UAS demonstrations. The primary focus is the availability and latency of the data delivered from the mesh array to the back office, with evaluation aligned to performance metrics outlined in the DO-377 standards document discussed in chapter 2. The goal of the demonstrations was to maintain communication availability exceeding 99.999 percent of the time during periods of active vehicle movement. In addition, the effectiveness of COTS equipment used in the demonstrations was evaluated, particularly its ability to provide accurate location awareness to support automated operations and mitigate conflicts. The project team also considered the customer perspective, specifically the perceived usefulness of the information delivered through the mesh array and its contribution to meeting the level of C5 needed for safe and efficient operations.

5.2 Method of Analysis

5.2.1 Data Visualization

The data points collected from the UAS demonstrations were presented and analyzed via data visualization. Data visualization is derived from log files generated by the equipment installed on the air vehicles during operations. As the vehicle moves, the equipment generates and records a data unit every 100 milliseconds, capturing key data elements, including the vehicle's latitude, longitude, and elevation at the time of each transmission initiation. These records of data payload in each transmission are recorded in the log files.

The visualization maps created from these collected data points provide insight into the spatial patterns of the communication and data transmission activities from the demonstration. The yellow dots in Figure 12 represent the location points from the transmit log file, indicating where transmission attempts were made from the vehicle. This demonstration was conducted as part of an extensive survey-type operation. Location points from the receive log file are plotted as green dots. Figure 13 shows the composite transmission and reception locations, representing locations where communication was successful. Any yellow dot not covered by a green dot indicates an area where a vehicle moving through the environment experienced a lack of communication availability. This is further illustrated in Figure 14,which provides a zoomed-in view of a particular area where several transmissions were not received.

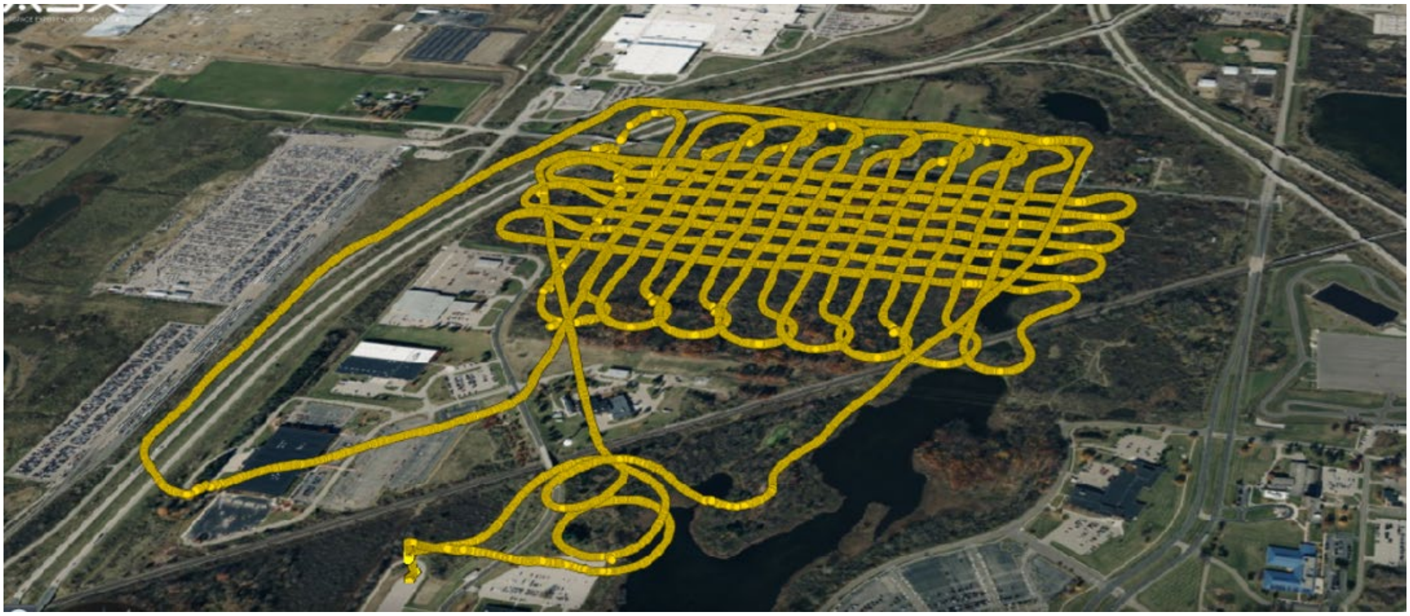


FIGURE 12. EXAMPLE BVLOS FLIGHT VISUALIZATION - EACH YELLOW DOT IS THE LOCATION OF A TRANSMISSION

FIGURE 13. EXAMPLE TRANSMISSION LOCATION YELLOW DOTS OVERLAYED WITH GREEN RECEPTION DOTS

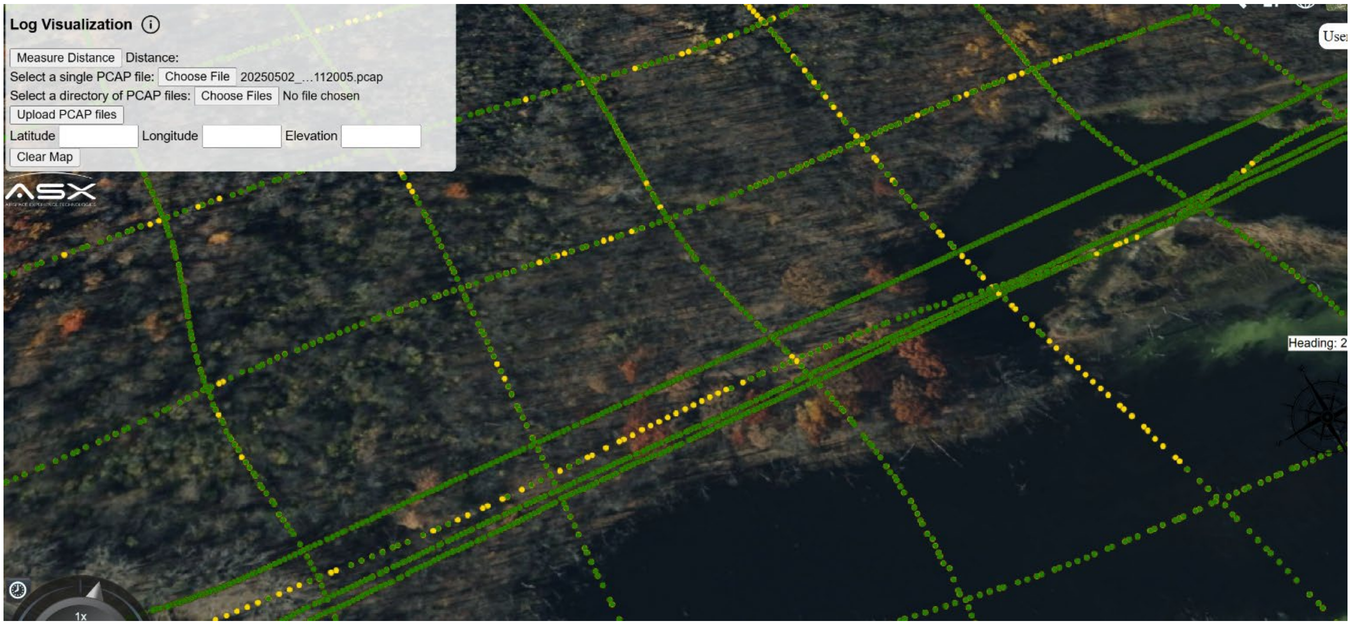


FIGURE 14. EXAMPLE YELLOW DOTS NOT COVERED BY GREEN DOTS, INDICATING AREAS WHERE COMMUNICATION WAS NOT AVAILABLE

Beyond whether communications are received or not, availability also considers the timeliness of the communication. An effective mesh communication network will actively receive communications from vehicles in a reasonably short amount of time. Logs from the Lansing MDOT facilities site demonstration were visualized to assess the timeliness of communication receptions to define the amount of time that would be considered reasonable. For each communication received from a vehicle by one or more ground stations, a point was plotted on the map shown in Figure 15 and color coded based on time from the last reception from that vehicle, according to Figure 16. This visualization provides information about the performance of the mesh communication network with the RSU siting as implemented.

FIGURE 15. OVERHEAD VIEW OF COMMUNICATIONS RECEIVED BY ONE OR MORE RSU; COLOR CODED BY TIME DELTA SINCE LAST RECEPTION

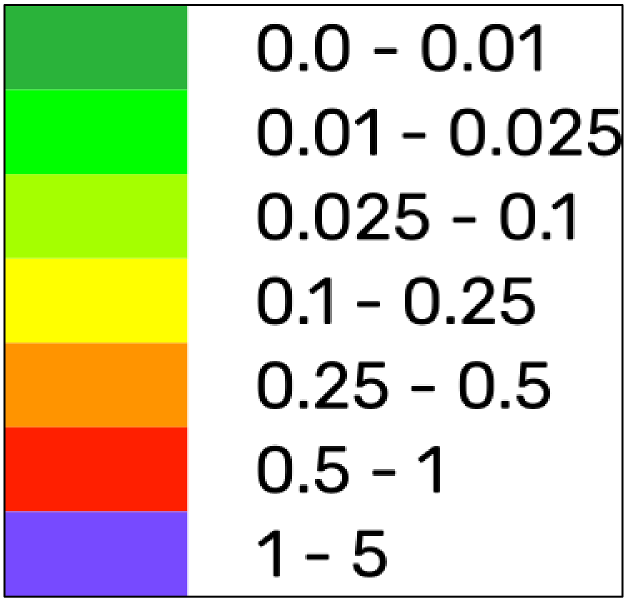


FIGURE 16. COLOR CODES FOR COMMUNICATION TIME DELTAS ON THE OVERHEAD MAP

While most communications were received in under 0.5 seconds, there were some periods of longer time deltas between messages received by a ground station. Figure 17 shows the location of communication gaps longer than 0.5 seconds. All of these longer reception gaps occurred in the northern section of the operating area, and it is clear that the denser vegetation in this region obstructed radio communication. A real-world implementation of this mesh network would require more densely sited RSU ground stations in this area to overcome the number of obstructions.

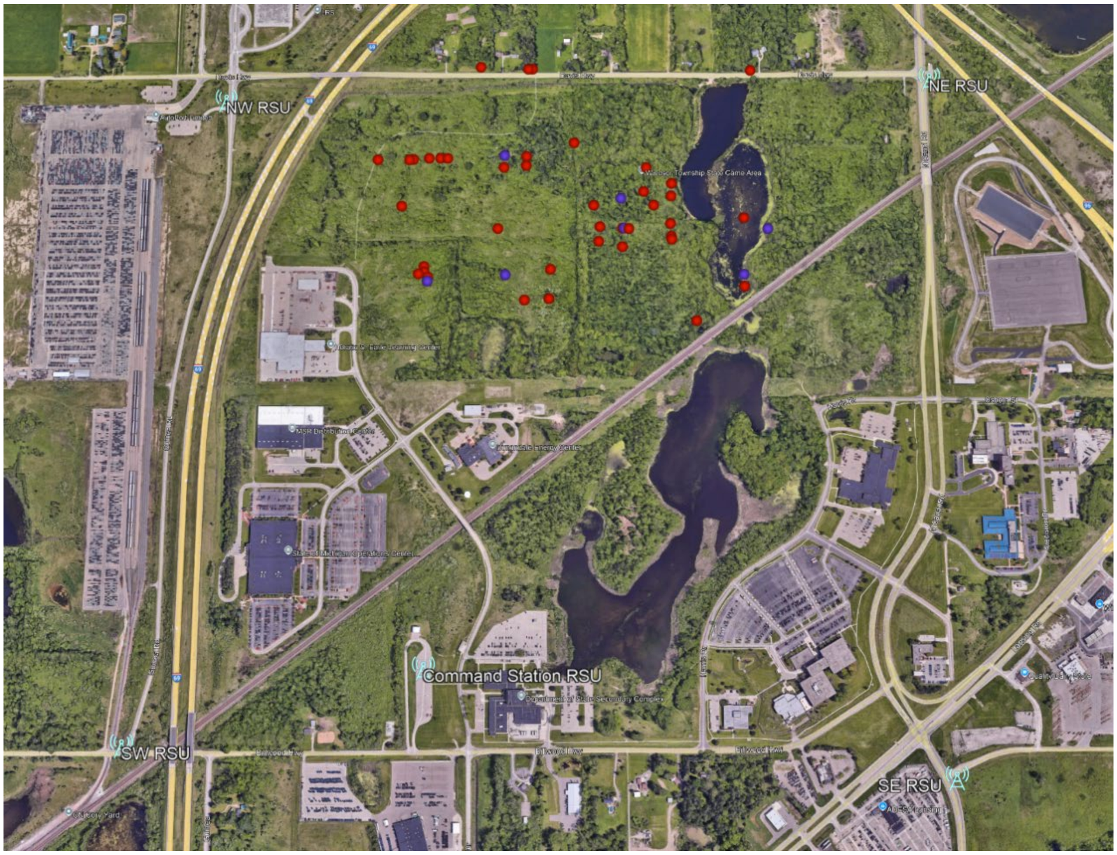


FIGURE 17. LOCATION OF COMMUNICATIONS RECEIVED WITH THE LONGEST TIME DELTA BETWEEN RECEPTIONS

5.2.2 **Statistical Analysis**

The data analysis is based on data collected from OBUs installed on multiple UAVs that transmitted to five RSUs installed on ground infrastructure. Two types of OBUs were used: C-V2X and DSRC. Some UAVs were conducting BVLOS operations, while others conducted traditional operations within visual line of sight (VLOS). This system is a mesh network, meaning that more than one RSU receives a single transmission. The analyzed data are divided into sections based on OBU type, operation type, and deduplication status.

Communication availability was the primary metric used to assess the performance of the UAS. Availability was calculated by examining the continuity of message receptions across flight operations. Availability was computed by measuring the time intervals (time deltas) between consecutive message receptions and identifying gaps where no message was received for more than a specific interval of seconds. Equation 1 shows the formula used for calculating availability.

Equation 1	Availability % = 1 - (gap count / (flight hours × (3600 / interval seconds)))

This process analyzed three different reception intervals: 0.5 seconds, 1 second, and 2 seconds. Any transmission in which the time between successive messages exceeded the specified interval was considered a gap. The total number of gaps was normalized against the expected number of message receptions throughout the flight operation. The total operation time for the three different operation types during the testing is provided in Table 1.

TABLE 1. FLIGHT TIMES DURING MARCH 2025 OPERATIONS

Operation Types	Total Operation Time
C-V2X BVLOS	2.2 hours
DSRC BVLOS	0.9 hours
DSRC BVLOS + VLOS	4.4 hours

The data set was segmented based on OBU type (C-V2X versus DSRC), operation type (BVLOS versus BVLOS + VLOS), and deduplication status (total versus unique). Deduplication was performed using a fully encoded message to eliminate multiple receptions of the same transmission across different RSUs in the mesh network. The resulting availabilities for each segment are presented in Table 2.

TABLE 2. COMPARISON OF AVAILABILITY METRICS

		C-V2X		DSRC			
		BVLOS		BVLOS		UAV	
		Unique	Total	Unique	Total	Unique	Total
Interval Seconds	0.5	99.659%	99.659%	98.580%	98.858%	99.809%	99.809%
	1.0	99.886%	99.886%	98.611%	98.796%	99.771%	99.771%
	2.0	100.000%	100.000%	99.198%	99.198%	99.847%	99.847%

DO-377 standards target 99.999 percent availability, meaning ground stations receive communications from vehicles within a predefined rolling time interval 99.999 percent of the time. The primary area of interest for this project is the availability of air vehicles, and Table 2 breaks down the availability of the different air vehicle segments based on 0.5, 1.0, and 2.0 second time intervals. This demonstration included a limited number of ground stations compared to an ideal real-world deployment. Real-world deployments by roadway owners/operators will have a higher density of RSUs than those deployed at the Lansing MDOT facilities site, which should increase system availability. Because the availability is already consistently above 98 percent and reaching as high as 100 percent with limited ground stations, this analysis suggests that the communication medium is likely to meet the availability requirements with the proper siting of infrastructure equipment.

5.3 Presentation of Results

5.3.1 **Coleman A. Young Municipal Airport**

RADIO SURVEY FLIGHTS IN OCTOBER 2024

RSUs were installed in three locations on existing infrastructure at DET (Figure 18). Sites were selected at the airport's north end, west side, and main terminal building to give potential radio communication coverage across the entire facility.

FIGURE 18. EQUIPMENT INSTALLATION AT DET

Figure 19 shows the expected radio coverage from the three ground RSUs. The yellow shaded volumes represent the expected radio coverage pattern, which extends approximately 1.5 km horizontally from each RSU and up to 400 feet above ground level (AGL) vertically. The overlapping coverage between the three RSUs enhances communication reliability within the shared area.

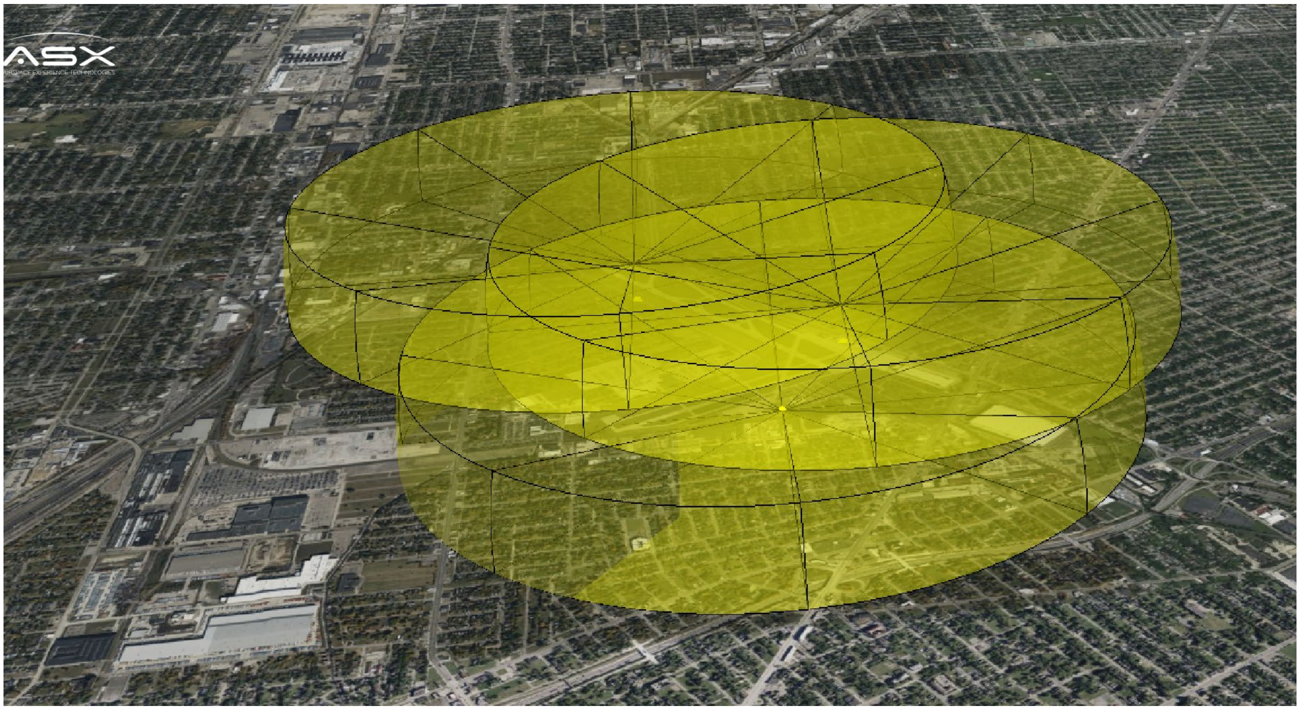


FIGURE 19. EXPECTED RADIO AVAILABILITY COVERAGE FROM RSUS AT DET

Several survey flights were conducted from the surface up to 350 feet AGL to confirm communication availability. Coverage visualization using receptions from the west RSU showed that communication was available from the surface to the highest altitude of the flight, as shown in Figure 20.

FIGURE 20. RECEPTION FROM THE WEST RSU SHOWS GREEN DOTS COVERING YELLOW DOTS FOR THE ENTIRE FLIGHT

However, radio communication was not consistently available down to the ground level when receptions from the north RSU were visualized as shown in Figure 21.

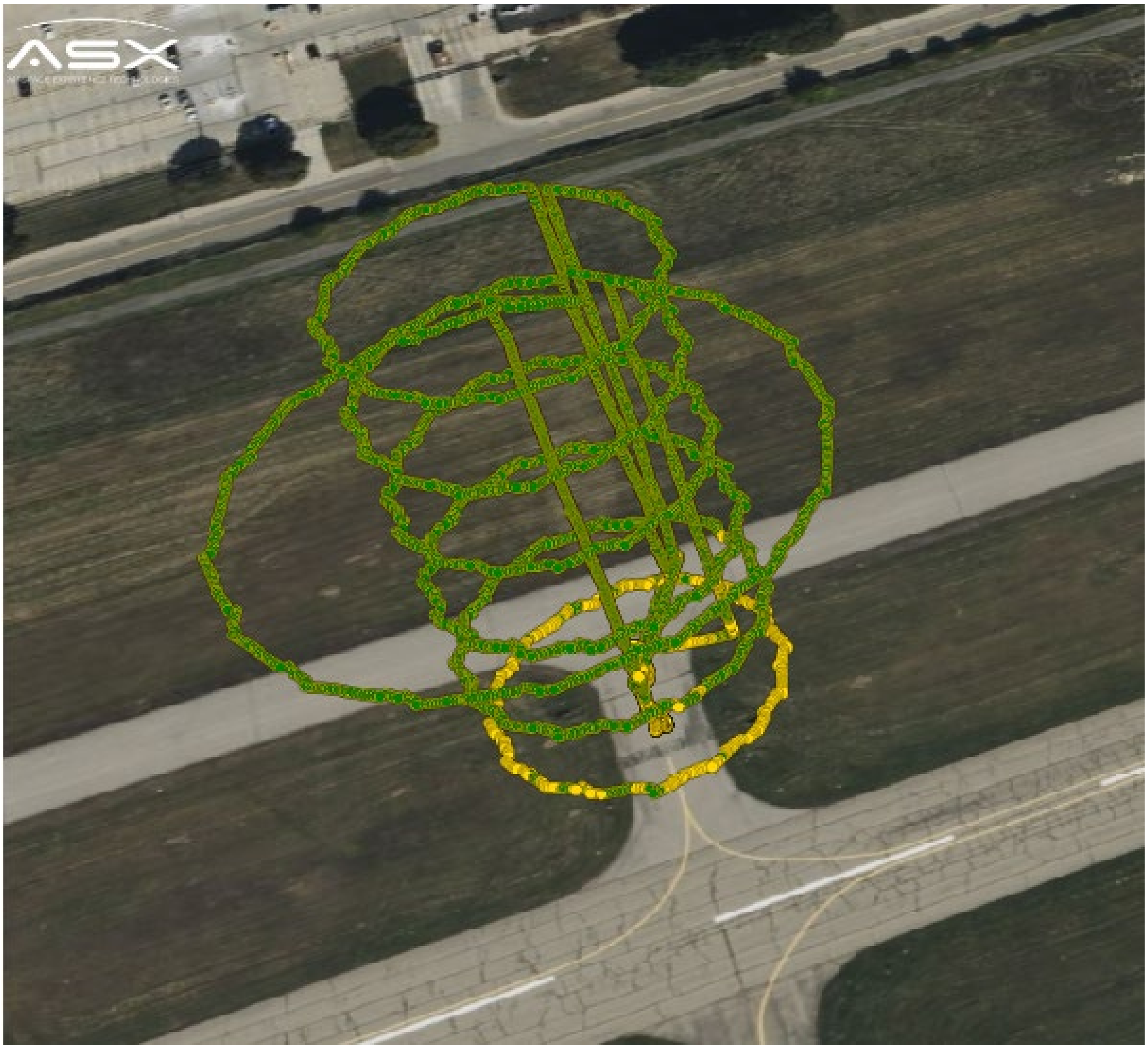


FIGURE 21. LACK OF AVAILABILITY OF COMMUNICATION FROM NORTH RSU

Examining the communication paths reveals that the north RSU's lack of communication availability can be explained. The path to the west RSU is unobstructed, while the path to the north RSU is obstructed by ground-level buildings and vegetation, as illustrated in Figure 22.

FIGURE 22. RADIO LINES OF SIGHT FROM NORTH AND WEST RSUS

5.3.2 Lansing MDOT Facilities Site Demonstration

NOVEMBER 2024 SURROGATE AIRCRAFT AND GROUND VEHICLE OPERATION

Temporary RSU ground stations were installed at the Lansing MDOT facilities site, and the equipment's operation was verified using OBU vehicle equipment installed in a surrogate aircraft (a Robinson R-44 helicopter) and surface vehicles. Figure 23 shows the installation of an RSU at the test site, and Figure 24 illustrates the location of the five RSUs installed.

FIGURE 23. RSU GROUND STATION AT THE SOUTHWEST CORNER OF THE TEST AREA

FIGURE 24. GROUND STATION LOCATIONS AT THE LANSING TEST SITE

The helicopter approached the test area from the northeast and conducted flight patterns at various elevations above 200 feet AGL, as shown in Figure 25. These flight maneuvers were designed to test communication coverage across the entire test site and identify locations where communication availability was reduced.

FIGURE 25. TRANSMISSION LOCATIONS FROM THE HELICOPTER ONBOARD RADIO DEVICE

Figure 26 shows where the surface vehicle drove multiple routes on arterial roads and adjacent freeways, covering the entire test site where obstructions such as terrain, buildings, and vegetation were present.

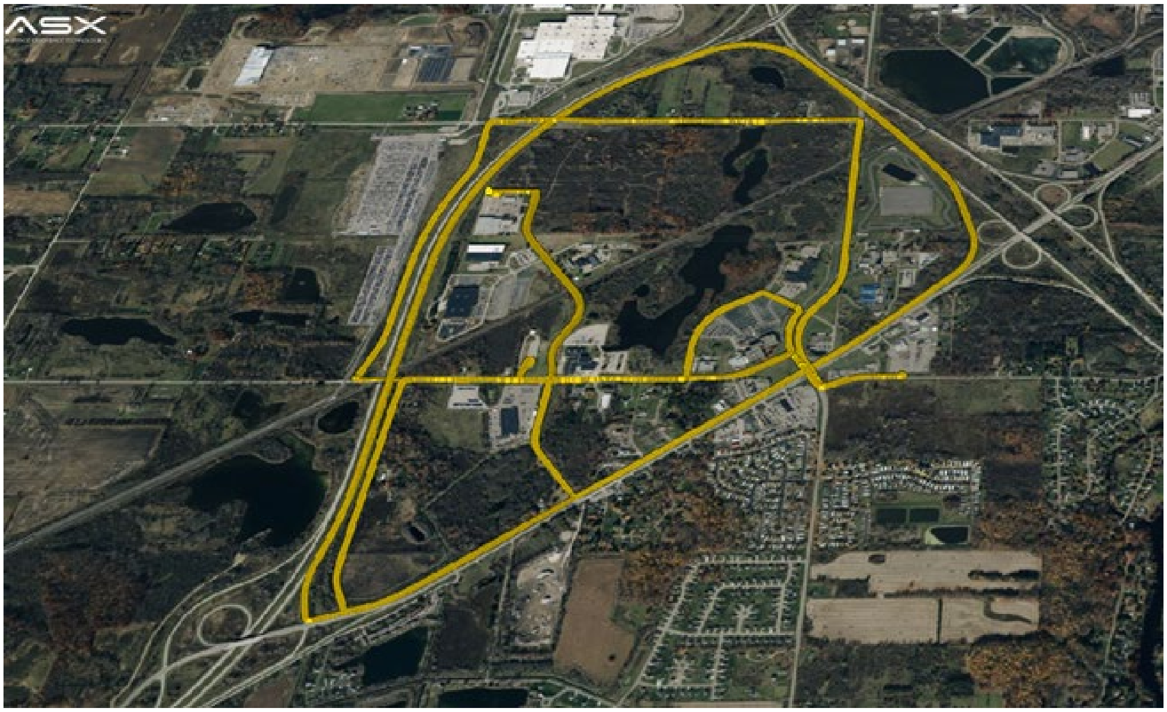


FIGURE 26. SURFACE VEHICLE LOCATION TRACKS

Overall, communication was available in the air except at the furthest distances from the ground RSU stations, as shown in Figure 27. Similarly, communication for ground vehicles was reduced when radio lines of sight were obstructed by terrain features, buildings, or vegetation. The testing helped highlight areas with potential signal degradation and provided insights for optimizing RSU placement to improve communication reliability.

FIGURE 27. COMPOSITE COMMUNICATION AVAILABILITY VISUALIZATION FROM AIR AND GROUND VEHICLE OPERATIONS

MARCH 2025 UAV AND SURFACE VEHICLE BVLOS

The ultimate goal of this testing at the Lansing MDOT facilities site was to demonstrate that the communication medium can support BVLOS UAV operations. RSUs were installed at the same locations shown previously in Figure 24. During this operation, both C-V2X and DSRC-type RSUs were used, with one of each type installed at each RSU location, as shown in Figure 28.

FIGURE 28. TEMPORARY RSU STAND WITH TWO RSUS - C-V2X TOP AND DSRC BOTTOM

Two extensive BVLOS flights were conducted using Sentaero 5 and Astro aircraft, both equipped with C-V2X radios. These two operations occurred simultaneously and were deconflicted through staggered takeoffs and by flying at different elevations. The Sentaero 5 flew nominally at 370 feet AGL in a survey pattern, while the Astro flew nominally at 250 feet AGL, conducting a simulated roadway inspection.

Figure 13 previously showed the combined communication availability visualization for these two operations using C-V2X. The close-up view in Figure 14 illustrates several communication gaps exceeding 500 milliseconds were observed. The statistical analysis presented in Table 2 above confirms the presence of these gaps and shows that the overall communication availability with gaps shorter than 500 milliseconds was approximately 99.66 percent of the time.

Another set of two BVLOS operations was conducted using a different FreeFly Astro UAV equipped with a DSRC radio, conducting a simulated railway inspection at a lower elevation of nominally 170 feet AGL. The path of the operation is shown in Figure 29.

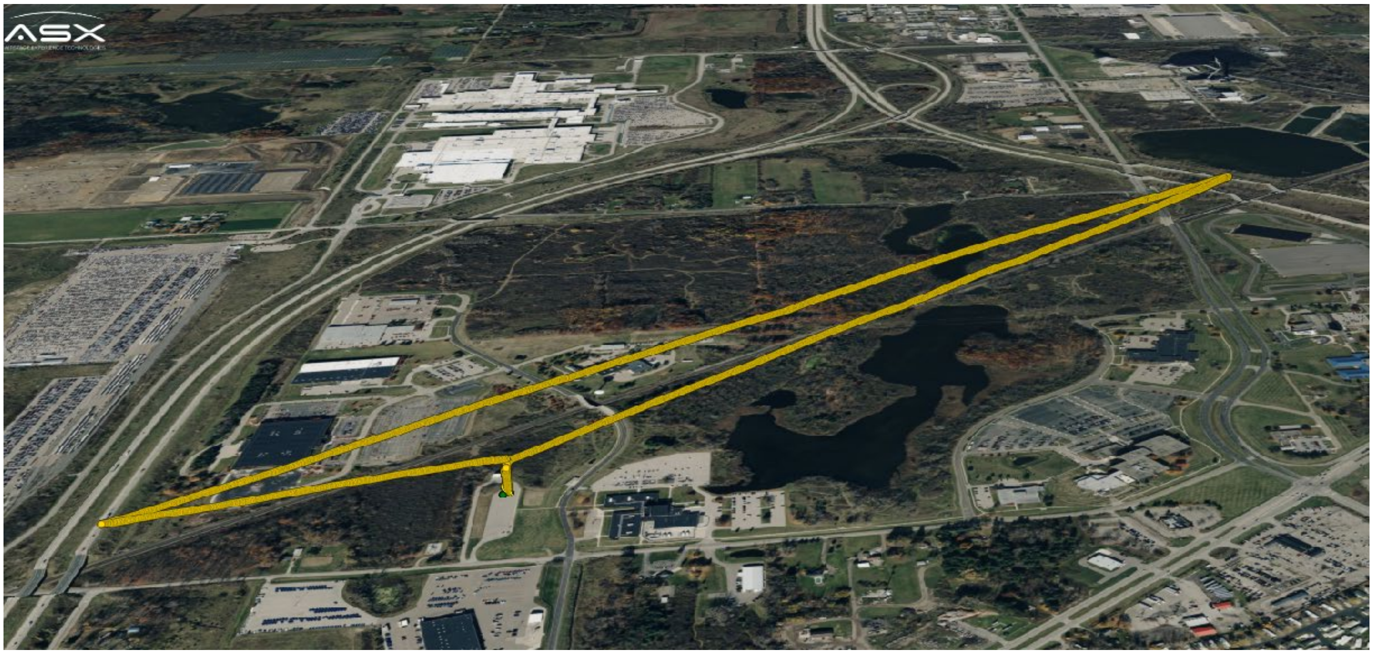


FIGURE 29. SIMULATED RAILWAY INSPECTION BVLOS FLIGHT USING DSRC

During this operation, there was a noticeable gap in communication availability in the center of the operating area, as shown in Figure 30. Some gaps in communication availability were also observed in the same area in the operations that occurred at higher elevations, but not to the same extent.

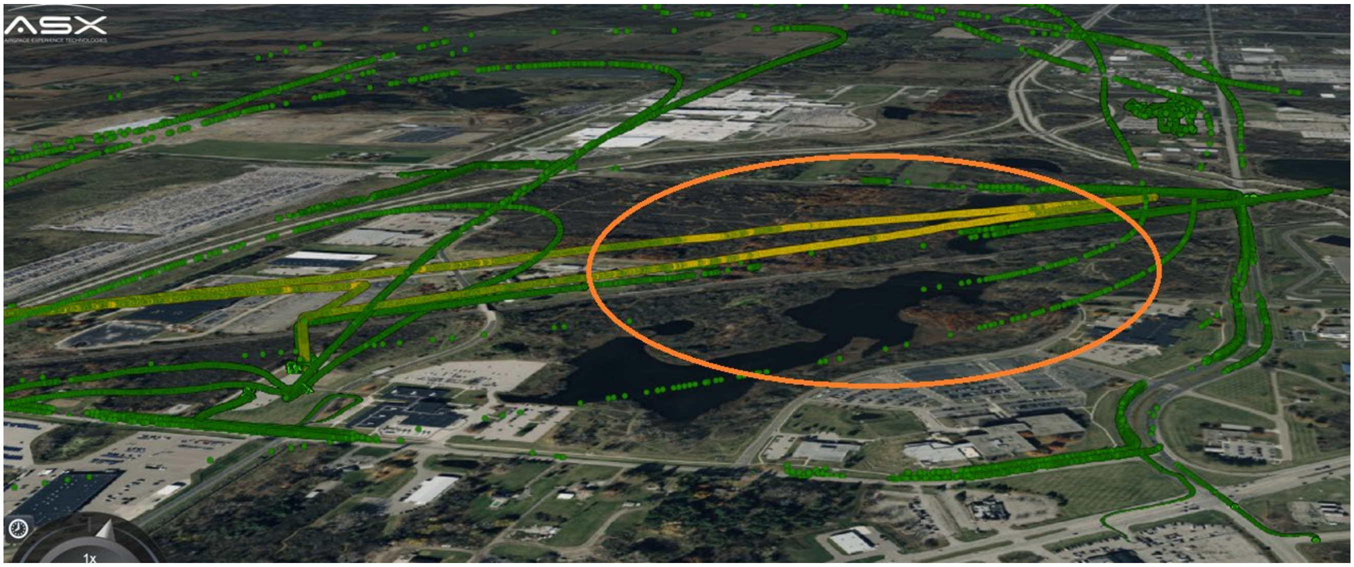


FIGURE 30. VISUALIZATION OF RAILWAY INSPECTION OPERATION SHOWING NOTICEABLE GAP ON COMMUNICATION AVAILABILITY AT THE CENTER OF THE OPERATING AREA

6. DISCUSSION

6.1 Validity of Hypotheses

The limited operations conducted at the Lansing MDOT facilities site demonstrated the underlying validity of the hypothesis that short-range wireless communication can be used to support command and control of BVLOS UAV operations. The successful transmission of data, along with the high percentage levels of communication availability achieved in both BVLOS UAV demonstrations, confirm that a mesh-based network using short-range wireless technologies such as DSRC and C-V2X can be a viable solution for enabling BVLOS UAV operations in real-world scenarios.

However, the results also highlight the importance of careful planning and deployment of ground-based radio equipment such as RSUs. The main factors affecting communication availability during the demonstration were the limited range of the equipment and its sensitivity to obstructions in the environment. Typical radios have a range of approximately 1.5 km in free space, but the signal strength is attenuated by terrain, vegetation, and buildings, especially near ground level. These limitations underscore the need for optimized RSU placement for consistent and reliable communication coverage.

Overall, the findings validate the hypothesis and highlight important considerations for the planning and deployment of UAV systems, which are essential for achieving reliable BVLOS UAV operations.

6.2 Implications

Surface transportation infrastructure owner-operators are planning to install radio equipment as part of their C-ITS. These systems are designed to enhance communication, coordination, and safety for surface transportation. The operations conducted at the Lansing MDOT facilities site demonstrated the promise of leveraging this same technology and communication medium for UAS operations.

As this communication infrastructure is deployed more widely, the same medium will become available for both air and ground vehicle management. This can allow for the seamless integration of UAS into existing ITS and enable multimodal coordination. This integration has the potential to improve situational awareness, operational efficiency, and safety across transportation networks.

The successful UAS communication mesh demonstration confirmed the feasibility of using this communication medium for UAS operations and paved the way for its inclusion in Michigan's broader mobility infrastructure.

7. CONCLUSIONS

7.1 Conclusions from the Study

The findings from the demonstration confirm that short-range wireless technologies such as DSRC and C-V2X can effectively support BVLOS UAV operations as well as multimodal operations with existing vehicles and infrastructure through mesh-based communication networks. While the results confirm the viability of this approach, they also emphasize the need for strategic planning and deployment of ground-based radio infrastructure, particularly to address the communication range limitations and obstructions from the environment. As connected ITS continue to evolve and be used widely, the integration of UAS operations into these existing systems and communication medium presents a significant opportunity to enhance multimodal coordination, operational efficiency, reliability, and safety. Continued deployment and optimization of the communication infrastructure is key to realizing the full potential of integrated air and surface vehicle operations.

7.2 Recommendations for Further Research

While the UAV operation demonstrations at the Lansing MDOT facilities site validated the viability of short-range wireless technologies for BVLOS and multimodal operations, further research is recommended to build on these findings. One recommendation is to conduct more systematic operations to gather comprehensive performance measures through three-dimensional UAV swarms. Three-dimensional swarms assess radio availability and study the cooperative behavior between UAVs, particularly in real-world environments where multimodal vehicles and physical obstructions such as other air vehicles, surface vehicles, and infrastructure are present.

Additionally, the availability of this communication technology opens up opportunities to explore and enable financial transactions and processing capabilities as a future application. Such applications have been widely used in Express Lanes by multiple agencies across the United States, enabling electronic tolling between infrastructure and vehicles to streamline traffic flow and improve efficiency in revenue collection.

Continued research in these areas will help establish a reliable and scalable communication network between UAS and surface systems and support the development of more efficient and coordinated transportation networks and services.

7.3 Recommendations for Implementation

This project demonstrated significant potential for advancing the future of UAS operations in both short- and long-range BVLOS operations through the use of commercial-off-the-shelf DSRC and C-V2X communication technologies. The project also showcased the potential for integrating UAVs with surface vehicles and existing infrastructure to enable a future connected transportation network that bridges aerial and surface transportation systems. This connected network could pave the way for serving as a digital or virtual visual observer to support BVLOS operations, allowing for safer and more efficient UAS operations.

Building on the successful outcomes of the MDOT UAS Communications Mesh Test Deployment project, the text below outlines practical next steps and recommendations to operationalize and scale the integration of UAS into Michigan's connected transportation infrastructure.

- **Expand Strategic Infrastructure Deployment**

  To achieve reliable, scalable communications coverage for UAS operations, MDOT and partner agencies should prioritize the strategic placement of RSUs along transportation corridors, urban centers, and critical infrastructure hubs. These locations should be selected based on terrain analysis, obstructions, line-of-sight mapping, and anticipated UAS flight paths. Coordinating RSU placement with ongoing ITS and connected vehicle infrastructure deployments will reduce costs and provide shared utility across modes. DSRC and C-V2X technologies are more cost-effective and flexible alternatives with significantly lower maintenance and replacement costs, making them a scalable solution for supporting a future communication mesh.

- **Pilot Aerial Mobility Corridors**

  MDOT should initiate a phased rollout of pilot aerial mobility corridors using the communication mesh framework validated in the demonstration. Priority corridors could include high-value use cases such as intercity medical deliveries, emergency response support, infrastructure inspections, and freight operations. These corridors should include both urban and rural segments to test diverse operational conditions and provide data for broader statewide scaling.

- **Conduct Advanced Operational Testing**

  Future testing should focus on three-dimensional UAS swarming operations to evaluate the mesh network's performance in complex, high-density environments. These tests would support more comprehensive modeling of communication resilience, cooperative vehicle behavior, and traffic deconfliction in multimodal settings. Emphasis should also be placed on how automated air and ground systems interact under shared command and control frameworks.

- **Integrate Financial and Data Services**

  As connectivity infrastructure is deployed, MDOT should explore opportunities to integrate financial transactions (e.g., electronic tolling, automated landing fees) and data services (e.g., telemetry logging, system health monitoring) into the mesh network. Leveraging use cases already proven in surface transportation can accelerate adoption and deliver new revenue streams.

- **Advance Regulatory and Industry Partnerships**

  Continued collaboration with the FAA, FCC, academic researchers, and private industry will be essential for scaling this system. MDOT should continue to work closely with these stakeholders to shape federal policy, guide national standards for communications infrastructure, and facilitate commercial adoption. Additionally, workforce training and stakeholder education should be embedded into the implementation to ensure operational readiness.

By following this implementation plan outline, MDOT can build on its leadership in intelligent transportation and lay the groundwork for a unified, multimodal system that safely and efficiently connects people and goods through both the ground and the air.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAM	Advanced Air Mobility
AGL	Above Ground Level
ASX	Airspace Experience Technology
ATC	Air Traffic Control
AVs	Automated Vehicles
BVLOS	Beyond Visual Line of Sight
CAV	Connected and Automated Vehicle
C2	Command and Control
C5	Command, Control, Communicate, Compute, Cyber
C5ISR	Command, Control, Communicate, Compute, Cyber, Intelligence, Surveillance, Reconnaissance
C-ITS	Connected Intelligent Transportation Systems
COTS	Commercial Off-the-Shelf
CTOL	Conventional Takeoff and Landing
CVIS	Cooperative Vehicle-Infrastructure Systems
C-V2X	Cellular Vehicle-to-Everything
DO-377B	Document-377B
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
km	Kilometer
LTE	Long-Term Evolution
MDOT	Michigan Department of Transportation

AAM	Advanced Air Mobility
MSP	Michigan State Police
NASA	National Aeronautics and Space Administration
NAS	National Airspace System
OBU	On-Board Unit
POE	Power Over Ethernet
RSE	Roadside Equipment
RSU	Roadside Unit
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
U-NII	Unlicensed National Information Infrastructure
USDOT	United States Department of Transportation
UTM	Unmanned Aircraft Systems Traffic Management
VLOS	Visual Line of Sight
VPN	Virtual Private Network
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle to Everything