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Request for Information on the National Spectrum Research and Development Plan

AERPAW

Response to "Request for Information on the National Spectrum Research and Development Plan"

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The AERPAW platform would like to thank the opportunity to respond to this request for information (RFI) on the National Spectrum Research and Development Plan[1]. Our views based on the issues raised in the RFI are as follows.

1. Recommendations on strategies for conducting spectrum research in a manner that minimizes unnecessary duplication, ensures that all essential spectrum research areas are sufficiently explored, and achieves measurable advancements in state-of-the-art spectrum science and engineering. This includes, but is not limited to, the following:

- **Methods/approaches to increase coordinated investment in R&D amongst government agencies, academia, civil society, and the private sector**
- **Structural and process improvements in the organization and promotion of Federal and non-Federal spectrum R&D**

Presently, there are four outdoor NSF PAWR platforms in the U.S. (POWDER, COSMOS, AERPAW, and ARA) which all have extensive capabilities related to spectrum measurements in various environments. Measurement data from these platforms for various spectrum related scenarios are being made publicly available by these platforms and new experiment types can be defined to collect data in various other spectrum related scenarios of interest. These platforms also allow running dynamic spectrum sharing (DSS) experiments in different environments, e.g. including scenarios that involve one or more autonomous vehicles. Such experiments can be initially developed in virtual environments in these platforms, where various fundamental research ideas on spectrum sharing and related artificial intelligence and machine learning approaches can be evaluated. The experiments can then be moved to real-world outdoor testbeds in bands that are supported by FCC experimental licenses.

Developing and operationalizing such platforms takes extensive effort that spans many years. As such, these PAWR platforms (and other similar large-scale outdoor wireless

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testbeds) are invaluable national assets, and they can be used widely by the research community for research and experimentation on spectrum technologies. The existing capabilities of PAWR platforms allow remote development of spectrum experiments by the national research community. By using these platforms, experimenters will save long years of development effort to achieve similar capabilities at other sites and will save funding resources to be invested on other related research efforts on DSS. There may be capability gaps in the existing PAWR platforms – a survey of capabilities and shortcomings of existing outdoor spectrum testbeds including PAWR platforms would help identify such gaps. Funding agencies may then consider funding projects (not necessarily to the original PIs operating those testbeds) to address those gaps, to help mature and sustain each outdoor platform for long-term utilization of those platforms.

2. Recommended priority areas for spectrum research and development, as well as productive directions for advancing the state-of-the-art in those areas. Areas of interest include, but are not limited to, the following:

- **Spectrum utilization efficiency**
- **Spectrum resilience and assured access for critical mission applications and passive scientific observation**
- **Dynamic spectrum access and management**
- **Spectrum situational awareness at scale**
- **Automatic and rapid mitigation of interference problems**
- **Modeling for coexistence analysis**

Topics relevant to each of the above include, but are not limited to, the following:

- **Technical methods, designs, and processes**
- **Economic-, market-, social-, and human-centric concerns**
- **Business and economic models**
- **Protection of citizen privacy, sensitive government missions, and business proprietary data**
- **Cost-effective hardware supporting more dynamic spectrum usage**
- **Use of artificial intelligence and machine learning techniques**
- **Testbed development**
- **Assessment and certification of advanced systems**

Use of AI/ML techniques for improving spectrum utilization and testing these approaches in real world environments is very critical. While cognitive radio and dynamic spectrum access have been researched by now for over two decades, it is rare to find real-world deployments of these technologies. The main reason is that the practical propagation constraints, hardware impairments, protocol and waveform aspects, among other factors, are commonly overlooked. Hence, approaches that may work great in simulations end up being impractical when they are tested in the real world. Valuable funding, as well as precious research and development resources, may be lost due to unrealistic modeling assumptions[2] that prevent deploying research ideas in real-world environments. To this end, investing in realistic digital twins that integrate real-world hardware and software constraints for the initial development and testing of DSS concepts carries a critical importance. Once the AI/ML-based DSS concepts are developed/tested in such digital twins, they can then be tested in their physical twin for real-world performance evaluation.

In Fig. 1, we explain the overall workflow for canonical experiments in the NSF AERPAW platform, which can be used for any DSS and spectrum monitoring experiments using real-world, open-source radio and vehicle (e.g. UAV) control software. AERPAW hosts various sample experiments that can serve as starting points for developing spectrum-related experiments in the digital twin. Experimenters can develop their experiments exclusively in a virtual environment, without having to visit the AERPAW platform in person, and AERPAW operations team deploys the experiments after the development is finished in the digital twin.

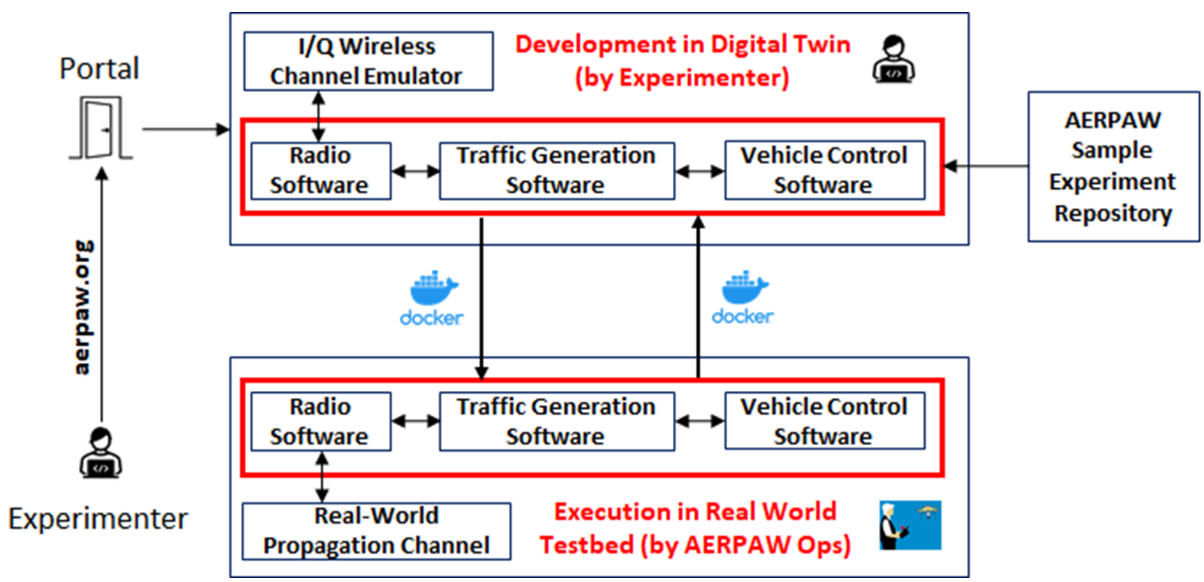

Figure 1: *AERPAW experiment workflow in development and testbed environments. Initially, an experimenter uses the digital twin to develop an experiment, then transfers the experiment to the outdoor testbed; the results are then returned to the digital twin.*

3. Recommendations on grand challenge problems for spectrum R&D. Grand challenges are selected research problems that if attacked will help motivate and coalesce R&D efforts. Such problems have the following characteristics:

[2] "All models are wrong. Some models are useful." G. E. P. Box, British Statistician.

- **The goal can be concisely articulated to stakeholders outside the field**
- **Success or failure is clear**
- **Achieving success requires advancing the state-of-the-art in multiple areas**

As discussed above, in our view, the development and validation of high-fidelity digital twins for spectrum-sharing applications (forming a tightly coupled pair with their outdoor physical twins) is one of the key grand challenges. If this grand challenge can be addressed, such digital twins can serve as shared development environments available to the broader spectrum research community for validating their AI/ML approaches, and seamlessly moving them to real-world testbeds. The success criteria for such digital twins is that if the same software experiment is executed in the digital twin and the corresponding physical testbed, observed system performance (e.g., spectrum sharing performance that can be characterized in various different ways) should be very comparable. AERPAW's outdoor testbed (physical twin) with locations of five towers and the corresponding flying field are shown in Fig. 2 and Fig. 3, respectively. The corresponding digital twin includes virtualized versions of these environments, including vehicles, radios, towers, and propagation conditions.

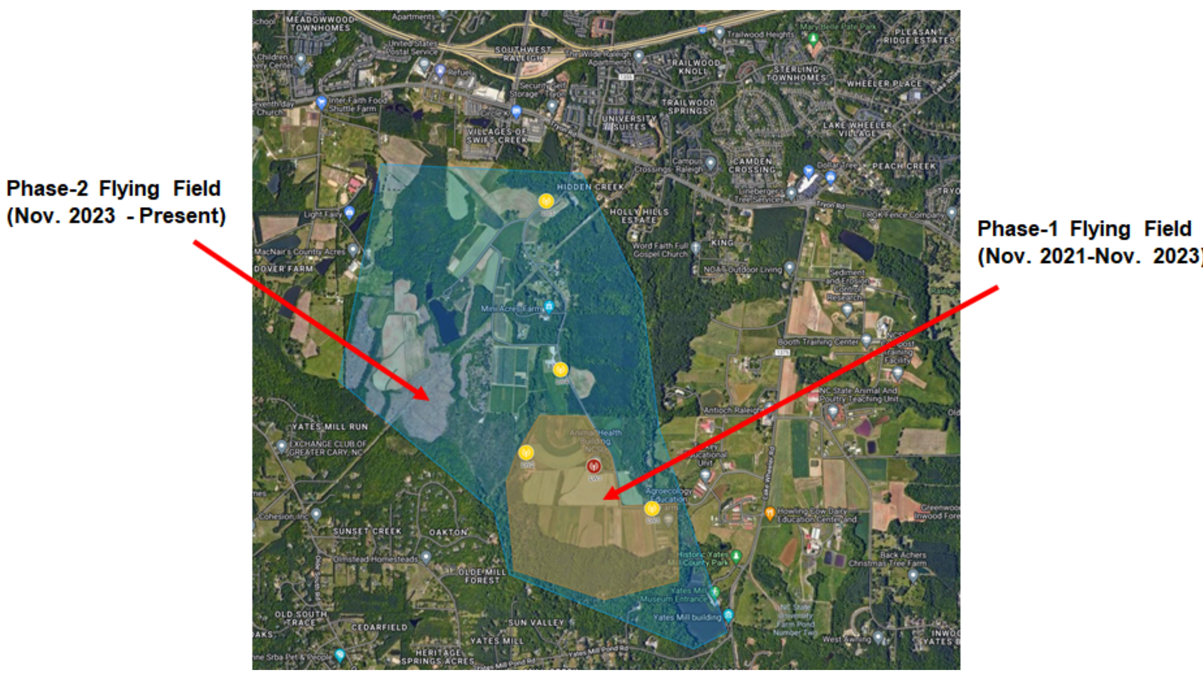

Figure 2: *AERPAW's UAV flying field in Lake Wheeler Field Farms, including Phase-2 extension of the flying field. The five radio towers provide radio coverage of the flying field using software defined radios. One of the towers is equipped with an Ericsson 4G/5G base station, while four of the towers include Keysight N6841A RF Sensors for real-time spectrum monitoring, signal classification, and signal source localization/tracking experiments.*

A major challenge to minimize the gap between the digital twin and the real-world testbed is to model the propagation conditions realistically in the digital twin, e.g. using ray tracing simulations. While the information about buildings can be downloaded and utilized from public websites such as OpenStreetMaps, and used in ray tracing simulations, other scatterers such as trees are not available in OpenStreetMaps and very difficult to model in a virtual environment. Such environments may require the use of Lidar scans to capture the information about all the scatterers, and scattered may vary across a year due to seasonal changes (e.g. due to presence/absence of leaves), changes in the environment (e.g. crops and farming equipment variations in the field), among other factors. To our knowledge, there are still major challenges in the effective integration of Lidar point clouds into ray tracing simulations for realistically modeling real-world environments in digital twins.

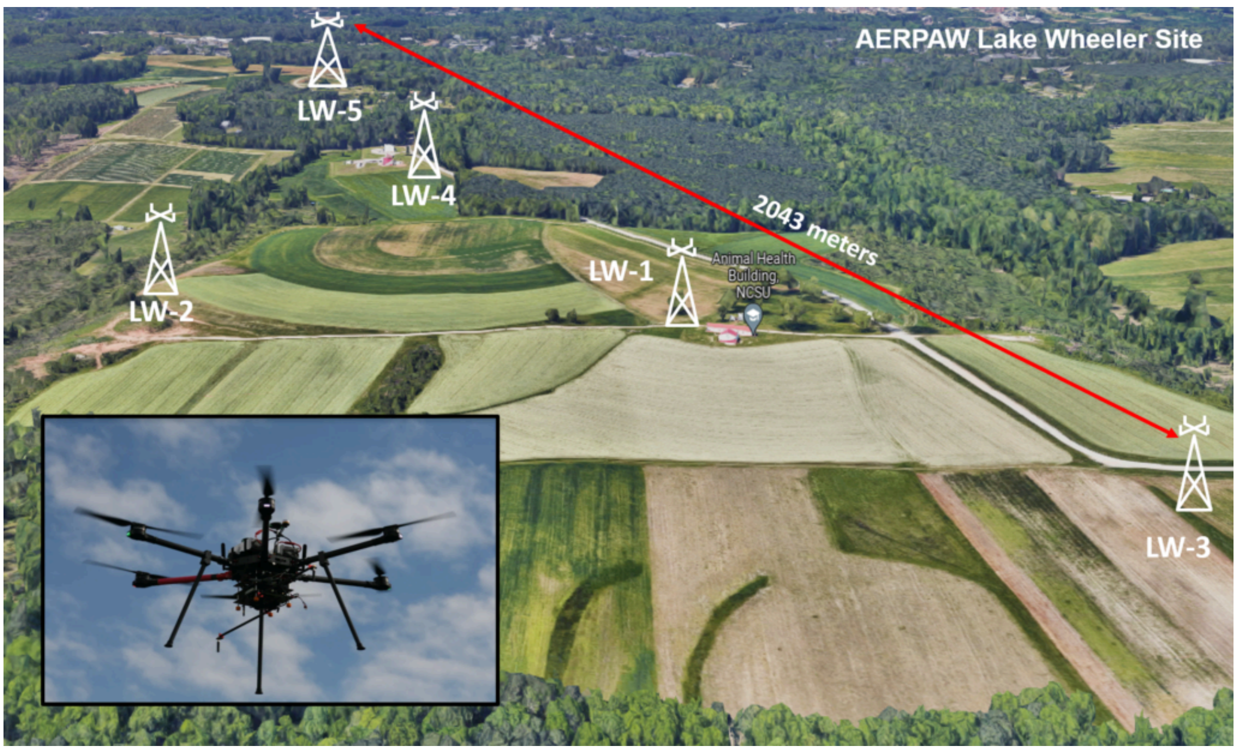

Figure 3: *AERPAW's UAV flying field in Lake Wheeler Field Farms and the five tower locations.*

4. Recommendations on spectrum R&D accelerators such as the following:

- **Shared public datasets**
- **Open-source software/projects**
- **Cost-effective flexible radio platforms**
- **Benchmarks and competitions**
- **Testbeds, research infrastructure, and collaboration support**

All these aspects are extremely important for minimizing duplication and enabling a shared development environment for the research community. As we have already commented earlier on the matter of open-source software projects, radio platforms, and testbeds, here, we will only comment on the critical need for public datasets, benchmarks, and competitions.

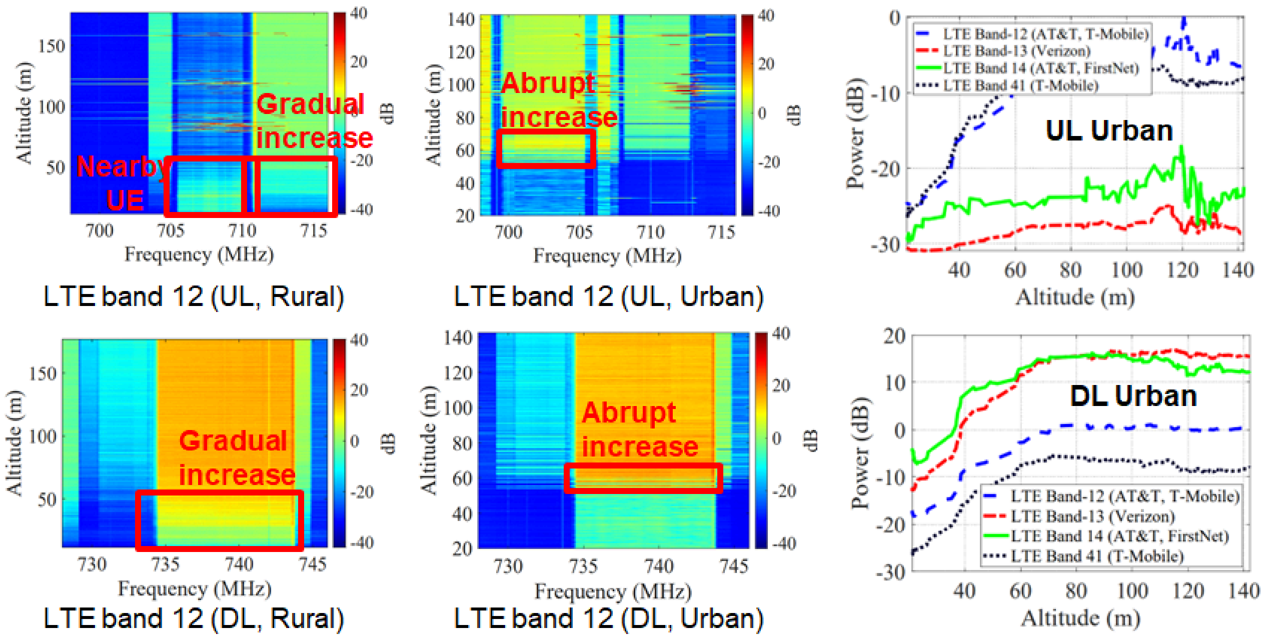

Figure 4: *Representative spectrum occupancy results versus altitude at LTE band 12 from one of the AERPAW datasets, considering both uplink (UL) and downlink (DL) in rural and urban environments. Similar datasets are available for all sub-6 GHz bands.*

Availability of public datasets in meaningful DSS environments is very important since they require a considerable expenditure of time and money (for equipment), as well as expertise not easily available. Making such datasets available, with detailed metadata and related post-processing scripts, will help the researchers with expertise in AI/ML techniques to test their DSS related ideas on real-world data rather than relying on over-simplified simulation tools. To give an example, spectrum measurements at a drone may rely on not only the 3D coordinates of the drone, but also the roll, yaw, and pitch of the drone (see Fig. 6), as well as the sensitivity of the spectrum sensor used at the drone. As such, knowing all this information in addition to the drone's 3D location can help develop not only more meaningful propagation and spectrum models but also more meaningful techniques for sharing the spectrum. There are already several publicly available spectrum data repositories, e.g. RF Data Factory as well as the datasets posted on the websites of individual PAWR platforms (see e.g. spectrum datasets by POWDER and AERPAW[3]). Identifying and addressing gaps in these datasets would be very beneficial for the research community. Fig. 4 shows example results based on the spectrum measurement datasets available on AERPAW's website.

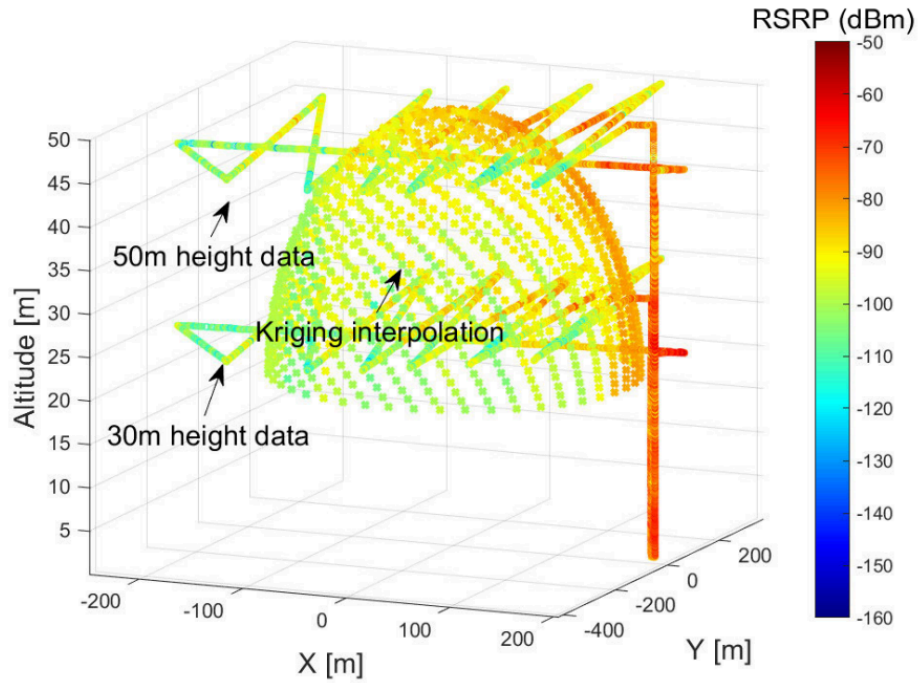

Figure 5: *3D spectrum mapping and interpolation using data collected at a UAV. Propagation data (or similarly, spectrum occupancy) at various UAV measurement locations can be interpolated across the 3D space, taking advantage of complex 3D correlation characteristics of such data, influenced by antenna factors, propagation conditions, and more[4]. It is worth to emphasize here that AERPAW platform (both the physical testbed and its digital twin) has unique ability to set in 3D space any configuration we want and hold it there for measurements: for example three transmitters on three drones at A,B,C and two receivers at D and E with certain antenna patterns on each of them.*

Competitions are also critical for coalescing the research community around a major problem. Competitions may be developed based on real-world datasets described earlier. Based on the data available on AERPAW's website, example dataset competitions that can be easily developed include: 1) 3D interpolation of spectrum occupancy or propagation measurements at UAVs using AI/ML techniques (see e.g. the results in Fig. 5 based on data collected from AERPAW environment); 2) localization of

[3] https://aerpaw.org/experiments/datasets/

[4] S. J. Maeng, O. Ozdemir, İ. Güvenç and M. L. Sichitiu, "Kriging-Based 3-D Spectrum Awareness for Radio Dynamic Zones Using Aerial Spectrum Sensors," in *IEEE Sensors Journal*, vol. 24, no. 6, pp. 9044-9058, Mar. 2024.

radio sources (e.g. jammers) based on measurements at a UAV; 3) classification of different types of UAVs and radio controllers based on radio recordings of the signals. Other competitions that may evaluate DSS techniques can also be developed but may require the data to be augmented with computer-generated data in space and time.

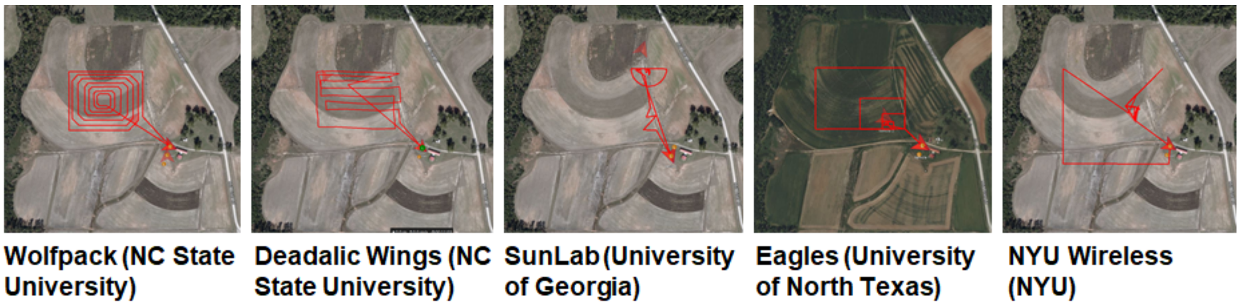

Figure 6: *Representative UAV trajectories from five AERPAW AFAR challenge teams, based experiments that are exclusively developed at AERPAW's digital twin. These trajectories are decided online by the UAV during the testbed execution based on signal strength measurements observed from the UGV.*

In addition to competitions that may rely solely on datasets, competitions that involve the development and testing of DSS software in digital twin and testbed environments can also be developed. This may e.g. include the development of AI/ML techniques for DSS with autonomous vehicles. A recent related competition organized by the NSF AERPAW platform is the AERPAW Find-a-Rover (AFAR) challenge[5]. In this competition, the goal for the competitors was to develop their AI/ML software for localizing an unmanned ground vehicle (UGV) in the development environment, where the trajectory of the UAV could be controlled dynamically based on signal observations from the UGV. Five different representative trajectories, each from a different team, are illustrated in Fig. 6, which show how the UAV can take different trajectory strategies for localizing the UGV based on the AI logic developed by the experimenters in the digital twin. After the experiment was developed and tested in the digital twin, it was subsequently deployed in the real-world testbed (the software containers are moved seamlessly, without changes, to the physical twin testbed).

Due to the difference between propagation environments in the digital and physical twins, the localization accuracy in the digital twin was more favorable in the AFAR competition when compared to that observed in the real-world testbed. Representative real-world measurements at UAV from one of the teams are shown in Fig. 7 for two different locations of the UGV, which show that the signal strength does not only depend on the location of the UAV, but also the relative orientation and tilt of the UAV among other factors, which should be characterized in a digital twin implementation. Careful

[5] https://aerpaw.org/aerpaw-afar-challenge/

observation of the results shows that the signal strength at the diagonal trajectory of the UAV is lower compared to the signal strength at the spiral trajectory for the first location of the UGV, while this behavior is reversed when the UGV location is relatively at a different direction as shown in the second figure. Such effects can be thoroughly characterized and calibrated.

As we commented earlier, closing gaps between the real world and digital environment, including (but not limited to) the effects similar to that described above, can be a grand challenge for the research community. This will not only provide more realistic performance observations in the digital twin, but it will also allow training of AI/ML algorithms in the digital twin based on realistic data before they get deployed in the real-world scenario.

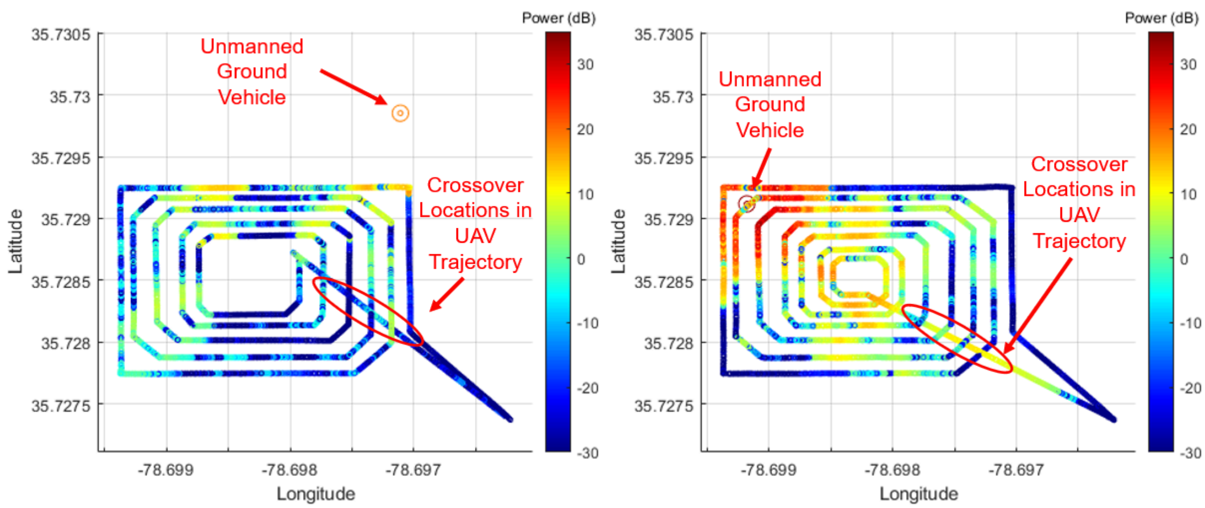

Figure 7: *Signal strength from two different unmanned ground vehicle (UGV) locations observed at a UAV's trajectory. The signal strength at cross-over locations are seen to be substantially different based on the direction, tilt, and relative position/orientation of the UAV with respect to the UGV.*

Similar to AFAR challenge experiment, various different DSS competitions can be developed in a digital twin, where experimenters can develop their DSS ideas first in the virtualized environment using real-world, open-source radio and autonomous vehicle software, and these experiments can then be seamlessly moved and tested in outdoor testbeds that are the physical twins of the development environment. Doing such competitions in a real testbed will ensure that none of the subtle details of communication protocols, waveforms, propagation conditions, vehicle trajectory control software, among other factors, are ignored, as may often happen in computer simulations or theoretical analysis.

5. Recommendations on near-term Federal activities to make progress towards anything identified in responses 1–4.

The federal government can: 1) invest in competitions in real-world testbed platforms to bring novel ideas from concept to reality; 2) invest in spectrum datasets, to identify what datasets are available and what are the gaps, and support efforts on generating specific datasets with rigorously documented metadata for enabling fundamental research by the broader community; 3) invest in developing high-fidelity digital twins that are specifically tailored to support AI/ML based spectrum sharing research and experimentation in diverse virtual and physical environments; 4) invest in research and development efforts that test DSS techniques in high-fidelity digital twins and their physical-twin testbeds.

6. Recommendations on a process to refine and enhance the R&D plan on an ongoing basis.

AERPAW team believes that seeking periodic (e.g., annual) feedback from the spectrum research community, similar to the process followed through this RFI, can help refine and enhance the R&D plan on an ongoing basis.

7. Terminology and definitions relevant for spectrum R&D.

- **One term of interest is "Dynamic Spectrum Sharing" which is a focus of the National Spectrum Strategy but was not defined.**

The concept of a "digital twin" should be defined rigorously for the DSS context, maybe including many of its variations. For the purpose of this document, we consider a digital twin to be a "development environment" where real-world software is programmed, e.g. radio software and drone software, in software containers. Many such software containers interact with each other by communicating through an I/Q channel emulator, in a fully virtualized environment. Such software can then be seamlessly moved to a testbed environment by moving the containers from the virtual environments to the computers at fixed towers and/or drones. There are other contexts where the term "digital twin" is used, e.g., not for development purposes, but in a real-time manner with an ongoing experiment, where each user equipment and base station may be connected to a digital twin to evaluate/predict network conditions and adapt their parameter configurations based on the conditions in the digital twin. There may be a need to define various aspects of "dynamic spectrum sharing" as it applies to experiment development in such a digital twin environment as well, such that the spectrum occupancy patterns resemble those in real-world environments.