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National Telecommunications and Information Administration
Washington, D.C. 20230

In the Matter of Implementation of the National Spectrum Strategy	))))	Federal Register Document Number: 2023-26810

COMMENTS OF THE NSF AERIAL EXPERIMENTATION AND RESEARCH PLATFORM ON ADVANCED WIRELESS (AERPAW)

The NSF Aerial Experimentation and Research Platform on Advanced Wireless (AERPAW) project appreciates the opportunity to respond to National Telecommunications and Information Administration (NTIA)'s request for input ("RFI") on the Implementation of a National Spectrum Strategy (NSS). Any inquiries related to this document can be directed to aerpaw-contact@ncsu.edu.

I. INTRODUCTION

The NSF AERPAW Platform is one of the four Platforms for Advanced Wireless Research (PAWR) projects funded by the National Science Foundation. AERPAW is the first wireless research platform to study the convergence of 5G technologies and autonomous drones. AERPAW offers its users an experimentation environment with programmable radio access network (RAN) technologies based on open-source software, commercial off-the-shelf hardware, and programmable unmanned aerial and ground vehicles (UAVs/UGVs) with 5G and beyond technologies. To that end, AERPAW is providing comments to the NTIA in the following sections: ***1) Brief overview of AERPAW and its spectrum related capabilities (Section II); 2)***

Some observations related to spectrum measurements and spectrum reuse based on recent airborne measurements at AERPAW infrastructure (Section III); and ***3) Recommendations for the implementation of NSS driven by our recent spectrum measurements and findings (Section IV).***

II. AERPAW OVERVIEW

The AERPAW platform was funded in September 2019 and its early experimentation capabilities became generally available in November 2021. These capabilities include channel propagation studies in sub-6 GHz bands, experimentation with LTE systems, and spectrum monitoring at fixed ground nodes as well as UAVs. Additional Phase-2 platform resources, sample experiments, and experimentation capabilities are soon to be released publicly in January 2024. The crucial part of AERPAW's physical resources include: (i) the RF environment and the airspace that the AERPAW operating areas represent; (ii) the physical equipment (SDRs, commercial RF equipment, fixed towers, UAVs, UGVs, and a helikite) that AERPAW provides to leverage those environments for experimental studies; and (iii) the expertise (and the required exemptions) in conducting such studies in compliance with FCC and FAA regulations that AERPAW represents. Physically, the testbed is hosted at sites in and around the NC State campus in Raleigh, NC. Central to AERPAW's unique characteristic is the availability of UAVs and UGVs in the testbed, where the trajectories of both types of vehicles can be programmed by the users of AERPAW, either following fixed waypoints or an artificial intelligence (AI) aided trajectory control algorithm that uses RF observations as its inputs. In conjunction with the programmable USRPs that are also available for direct programming by the researchers, as well as other real-world, commercial radio equipment, this provides the NextG wireless researcher a facility for research experiments not practicable in any other facility at this time.

Fixed Nodes, Portable Nodes, and Vehicles: At a very high level, the facility includes eight tower locations (fixed nodes), at each of which some combination of AERPAW programmable software-defined radios (SDRs) and commercial radio equipment (such as an Ericsson 4G/5G base station, multiple Keysight RF sensors with spectrum monitoring and signal decoding capabilities up to 6 GHz, and LoRa gateways) are permanently installed. The SDRs are controlled by servers, or companion computers (CCs), installed in each location that also offer edge-computing capabilities. These fixed node locations are distributed over the extensive Lake Wheeler Agricultural Fields of NC State University, and some nodes are also installed in the Centennial Campus of NC State University. The complement of these fixed nodes are AERPAW's portable nodes, also consisting of a computer and SDR(s), but smaller ones so that an AERPAW portable node can be mounted on a UAV/UGV. The CC on a portable node, an Intel NUC, also controls the UAV/UGV itself. A smaller version of the portable node that can get carried at the smaller UAV is also available, to do experiments with mobile phones and LoRa sensors that are connected to a LattePanda as the CC. More information on AERPAW is available at the AERPAW Facility website (aerpaw.org) and the User Manual linked therefrom, and previous publications including [1]. A list of representative recent references related to AERPAW are available at https://aerpaw.org/publications/.

III. OBSERVATIONS FROM RECENT SPECTRUM EXPERIMENTS AT AERPAW

The AERPAW team recently conducted a series of airborne spectrum monitoring and propagation experiments using its helikite and drone platforms. The key related references can be found at [2-12] and we believe that *some of the findings in these studies are very relevant to the implementation of the NSS*. In this section, we will provide some key observations from these recent spectrum measurements and propagation studies. Further discussions and related measurements can be found at our corresponding publications. Note that while most of the specific bands we considered in these publications are 4G/5G licensed bands that are readily used by cellular providers, our conclusions can be generally applicable to other bands that may be opened to sharing with cellular technologies in the future.

Observation 1: Spectrum Occupancy Increases with Altitude. Our related representative results based on the measurements from [6] are presented in Fig. 1. While these results are provided as examples for four specific LTE bands, in almost all the bands that we studied, including various different 4G and 5G bands and the ISM bands, *the spectrum occupancy increases with altitude of the helikite*, up to altitudes of 140 meters. How much the spectrum occupancy changes with the altitude varies a lot depending on the specific band, whether that band is downlink (DL) or uplink (UL), and whether the environment is urban or rural, among other factors.

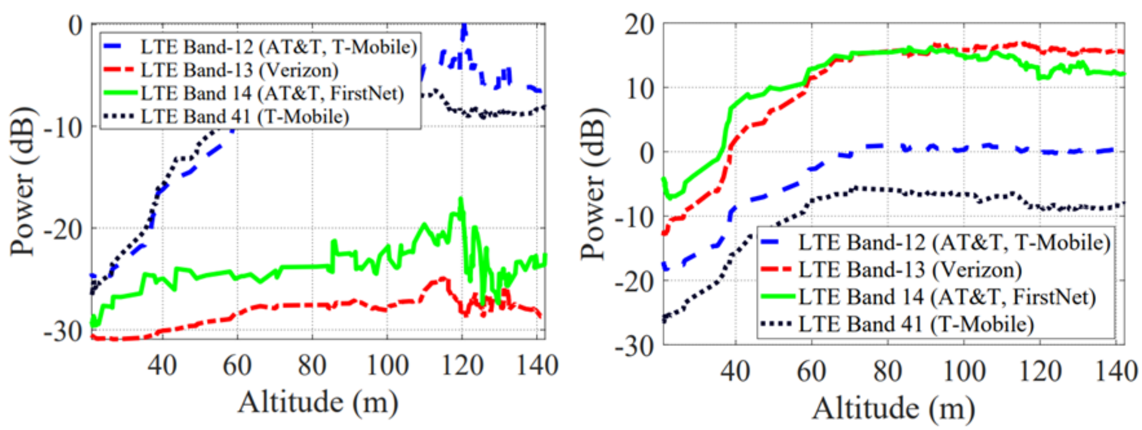
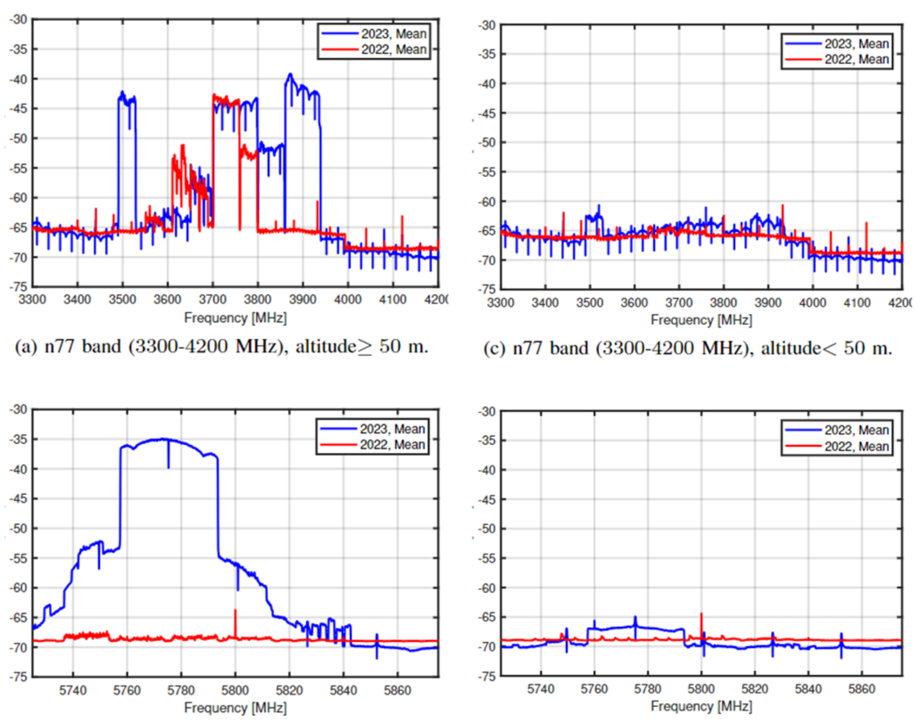


Figure 1: Aggregate spectrum occupancy versus altitude at four different LTE bands. (Left) Uplink in an urban environment, (Right) Downlink in an urban environment.

The main reason for the increased spectrum occupancy is the higher probability of line of sight with the signal sources as the altitude increases: the aggregate power from all the transmitters increases with altitude, since the receiver moves into line of sight with a larger number of signal sources. *More measurements at higher altitudes are needed* to observe better when the effect of path loss starts to dominate the effect of increased probability of line of sight.

Observation 2: Spectrum Occupancy Changes Captured Better at Higher Altitudes. Due to the higher probability of line of sight, we observed (see our representative results from [3] presented in Fig. 2) that spectrum occupancy is significantly more “visible” at altitudes above 50 meters compared to altitudes below 50 meters. The height above 50 meters here is when our helikite clears reasonably above the buildings around it, while the threshold altitude may be different for other urban environments. Regardless, <u>*spectrum occupancy measurements should be done at sufficiently high altitudes*</u> to understand how the spectrum trends change over time. Measurements at ground level or even at towers that are not sufficiently high may provide misleading conclusions about spectrum occupancy trends, especially at airborne receivers or at highrise buildings.



(a) n77 band (3300-4200 MHz), altitude$\geq$ 50 m.

(c) n77 band (3300-4200 MHz), altitude$<$ 50 m.

(b) ISM band (5725-5875 MHz), altitude$\geq$ 50 m.

(d) ISM band (5725-5875 MHz), altitude$<$ 50 m.

Figure 2: Spectrum occupancy measurements at 3 GHz and 5 GHz bands: (a) and (b) are at helikite altitudes ranging between 50 meters and 150 meters, while (c) and (d) are at helikite altitudes below 50 meters.

Observation 3: Occupancy vs Altitude Varies in Rural and Urban Environments. Our representative results from [6] are presented in Fig. 3 for LTE band 12, which show that <u>*in urban*</u>

environments, spectrum occupancy changes abruptly with altitude, while *in rural environments, spectrum occupancy increases more gradually*. This is because in an urban scenario, the helikite was surrounded by buildings as high as 50 meters, and as soon as the helikite climbed above the buildings, the occupancy increased very quickly. On the other hand, our rural area is an open area where there were not many blockages between the helikite and the signal sources other than trees that are at least several hundred meters away from where the helikite was launched from. Moreover, in the rural area, the spectrum occupancy is higher at lower altitudes, while in the urban environment, the spectrum occupancy is higher at higher altitudes. Additional results on spectrum occupancy probabilities for a variety of 4G/5G/other bands are available at [6]. Differences in uplink and downlink spectrum occupancies are also clearly visible; e.g., in uplink rural environment, there is a nearby mobile phone that is scheduled to transmit in the 705-710 Mhz band, and as the helikite's altitude increases, spectrum occupancy decreases gradually as the helikite moves away from the mobile phone.

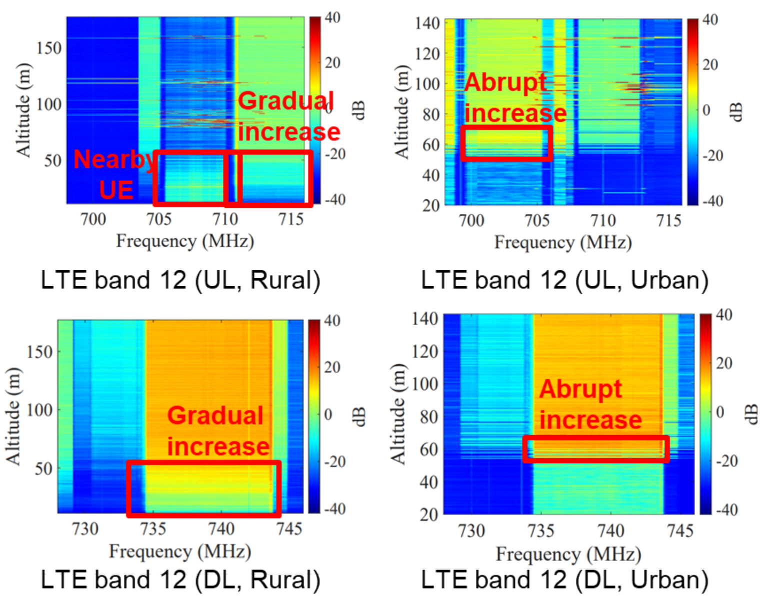
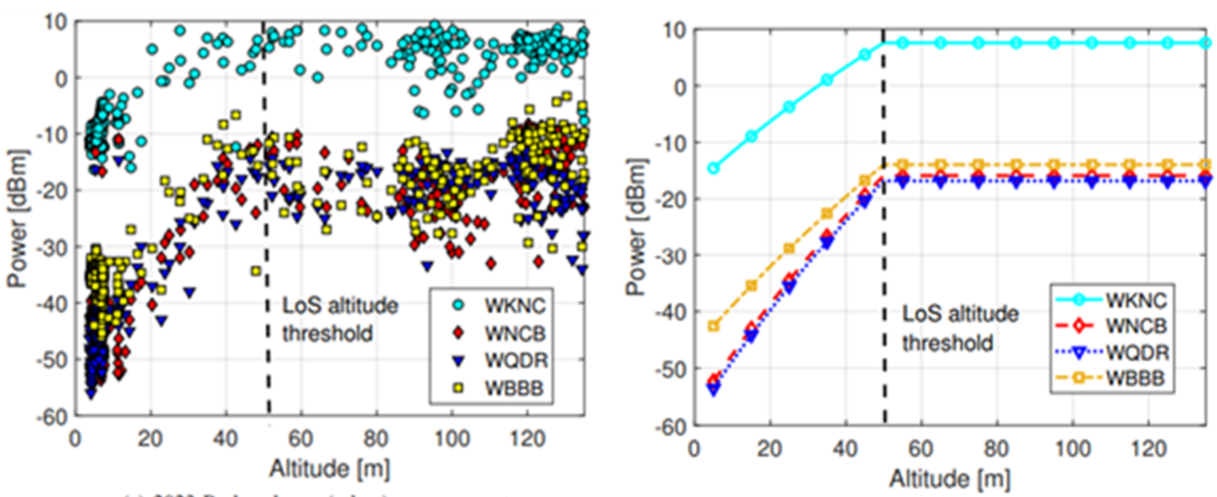


Figure 3: Comparison of spectrum occupancy trends in rural and urban environments with respect to the altitude (y-axis), for downlink and uplink scenarios.

Observation 4: Spectrum Sharing Opportunities in Time, Frequency, Space. As can be seen in Fig. 3, *there are pockets of spectrum sharing opportunities in time, frequency, and* *spatial (altitude) dimensions*. For some cases, the transmitter(s) may be a mobile phone(s) on the ground with lower transmit powers (possibly using uplink power control which may further reduce transmit power in some cases), and at higher altitudes the spectrum occupancy may be limited due to path loss and propagation characteristics. Hence, considering a frequency division duplex (FDD) system, the uplink spectrum can be reused by receivers at high enough altitudes, assuming transmissions from other nearby mobile phones are far away. For some other cases, the transmitter(s) may be base station(s) at far away locations, hence receivers on the ground with sufficient isolation through buildings may be able to reuse the spectrum. Spectrum allocation approaches such as those involving dynamic spectrum reuse and spectrum access system (SAS), and approaches that take advantage of AI/ML techniques, can be deployed to improve spectrum utilization while also satisfying the quality of service requirements and interference sensitivities of the users in the environment.



(a) 2023 Packapalooza (urban) measurement.

(b) 2023 Packapalooza (urban) analytical results by (1).

Figure 4: Air-to-ground propagation modeling at FM radio bands. (Left) Measurements from four different FM radio bands as a function of helikite altitude. (Right) Analytical spectrum occupancy models characterizing the spectrum measurements on the left, taking advantage of the knowledge of FM radio transmitters (transmit power, location, height).

Observation 5: Knowledge of Signal Sources can Help in Spectrum Modeling. In [4], we provide a case study of air-to-ground propagation modeling and spectrum occupancy characterization with FM radios. Representative results are provided in Fig. 4. Results show that *reasonable characterization accuracy is possible with analytical altitude-dependent propagation models, which can be used to develop dynamic spectrum reuse techniques*. A more sophisticated model can be developed for cellular bands, e.g., taking advantage of the crowdsourced data available at websites such as cellmapper.net, to extract locations and transmission configurations of cellular towers. Our additional measurements on RSRP and RSRQ (not included here) from specific base stations also show that RSRP gets better with altitude while RSRQ gets worse due to higher interference observed from other interference sources as the altitude increases.

We have also carried out experiments by capturing I/Q samples at UAVs from AERPAW's towers, while they are transmitting 4G and 5G signals, see e.g. [2,5,7,8,9,11]. Kriging-based signal interpolation can help considerably improve occupancy modeling from a specific signal source, e.g. [2,7]. Further measurement-based and analytical studies are needed to explore how well spectrum interpolation can work with multiple transmission sources, with/without partial knowledge of transmitter characteristics, and with different densities of spatial and temporal measurements at UAVs.

Observation 6: Digital Twins Can Help with Spectrum Reuse Research. Spectrum monitoring experiments we have carried out in AERPAW are designed to capture data a in specific manner. For example, due to the limited bandwidth of the SDRs, the spectrum between 85 MHz to 6 GHz is swept with a specific bandwidth resolution. In some cases, we capture I/Q samples at every 20 milliseconds out of each 100 milliseconds duration, as continuous sampling results in dropped I/Q samples. There may be various related design aspects to how spectrum monitoring should be specifically carried out. *Initial development for spectrum monitoring experiments can be done and tested extensively in a digital twin* that executes real-world software in a virtual environment before they get deployed in the real-world testbed (see e.g. [1]

about AERPAW's experiment workflow with both environments). It is important that the digital twin uses realistic enough propagation models; e.g., capturing the effects of buildings and trees becomes critical for air-to-ground propagation studies, and LIDAR-based point cloud data may be used to improve propagation modeling accuracy through ray tracing simulations.

In addition to spectrum monitoring, AI/ML based dynamic spectrum-sharing technologies can be developed tested first in a digital twin environment, as real-world testing is considerably more complicated and costly. After sufficient development and testing are done in a digital twin and the experiment reaches a reasonable maturity, they can be subsequently deployed in the real-world twin.

IV. Recommendations for the Implementation of NSS

Recommendation 1: Extensive Airborne Measurements are Needed at Dedicated Spectrum Measurement Testbeds. To better characterize spectrum occupancy, AERPAW team recommends *carrying out extensive airborne measurements in diverse environments and conditions*. It is important to do measurements at higher altitudes to better capture the interplay between path loss and the probability of line of sight. The four PAWR platforms (POWDER, COSMOS, AERPAW, ARA) are outdoor testbeds that are uniquely positioned for generating spectrum occupancy data for the implementation of the NSS. In particular, AERPAW fits ideally for collecting spectrum measurement data from UAVs and a helikite, in rural, sub-urban, and urban environments. AERPAW has/pending experimental licenses (and is seeking an FCC Innovation Zone amendment) in 3100-3450 MHz and 5030-5091 MHz bands and can support spectrum measurements and propagation studies in these bands that are part of the NSS. Experimentation capabilities on the ground are also available covering the whole 37-37.6 GHz spectrum, while some development effort would be needed for doing air-to-ground experiments for this millimeter wave spectrum. Any collected spectrum data should be documented rigorously along with all the relevant metadata (e.g., using SigMF data format), and made publicly available to nationwide researchers so that they can develop spectrum sharing techniques building on realistic datasets. AERPAW has been releasing spectrum measurement data through https://aerpaw.org/experiments/datasets/, and will continue adding new datasets as they become available.

Recommendation 2: Site, Band, UL/DL, and Scenario Specific Occupancy Models. Building on the real-world spectrum datasets, and other supplementary information such as the locations and transmit powers of cellular base stations, more accurate altitude-dependent spectrum occupancy and propagation models can be developed for various scenarios and environments. The availability of such realistic models will then help the research community to test AI/ML aided dynamic spectrum sharing techniques using meaningful modeling assumptions. The AERPAW team recommends that the *NSS implementation plan supports the development of data-aided spectrum occupancy and propagation models* for a wide variety of scenarios, including at different altitudes, different dupplexing models and UL/DL configurations, for different deployment environments, and different bands in consideration by the NSS.

Recommendation 3: Use of Digital Twins for Spectrum Reuse Experiment Development and Testing. As it is complicated and costly to do spectrum reuse experiments in outdoor environments, AERPAW recommends that *NSS supports digital twin environments for developing spectrum monitoring and sharing experiments*. It is critical that experiments developed in such digital twins can be smoothly moved to their real-world counterparts. This requires the following: 1) radio (SDR), wireless traffic, and vehicle software developed in the digital twin should be those that will eventually get deployed in the real-world testbed, rather than relying on simplified models and assumptions (e.g., ray tracing simulations in MATLAB), so that real-world behavior can be accurately captured as they are exactly developed in the digital twin, and experiments can be quickly moved to a testbed environments once the development is finished; 2) propagation environments in the digital twin should be as close as possible to those in the real-world counterpart. The AERPAW platform satisfies requirement #1 and it is working on improving its propagation models in #2.

All in all, we believe there is a critical need for spectrum testbeds for the successful implementation of the NSS, and the PAWR platforms are ideally suited for this purpose with their diverse propagation environments. Among the PAWR platforms, AERPAW is a national testbed that is uniquely suited for airborne spectrum measurements and can support experiments in its tightly interconnected digital twin and real-world testbed environments. AERPAW is seeking extensive expansions to its FCC Innovation Zone that spans Sub-6 GHz and millimeter wave bands and is working closely with the National Radio Dynamic Zone community. Spectrum measurements can be carried out up to 400 feet with UAVs (500 feet with helikite), while higher altitudes up to 1000 feet can be possible after getting necessary approvals from the FAA. We look forward to supporting the implementation of the NSS at AERPAW.

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