# Open RAN testbeds with controlled air mobility

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## ARTICLE INFO

## ABSTRACT

With its promise of increasing softwarization, improving disaggregability, and creating an open-source based ecosystem in the area of Radio Access Networks, the idea of Open RAN has generated rising interest in the community. Even as the community races to provide and verify complete Open RAN systems, the importance of verification of systems based on Open RAN under real-world conditions has become clear, and testbed facilities for general use have been envisioned, in addition to private testing facilities. Aerial robots, including autonomous ones, are among the increasingly important and interesting clients of RAN systems, but also present a challenge for testbeds. Based on our experience in architecting and operating an advanced wireless testbed with aerial robots as a primary citizen, we present considerations relevant to the design of Open RAN testbeds, with particular attention to making such a testbed capable of controlled experimentation with aerial clients. We also present representative results from the NSF AERPAW testbed on Open RAN slicing, programmable vehicles, and programmable radios.

## 1. Introduction

### 1.1. Open radio access network

Open RAN has emerged as a serious and perhaps critically necessary alternative to the proprietary Radio Access Network (RAN) solutions that have characterized cellular networks. Multiple organizations and consortia have announced initiatives and move towards Open RAN; in particular, the O-RAN Alliance has proposed a series of specifications that have gained significance in providing a possible single standard for Open RAN activities. The open architecture of Open RAN, and the definition of interfaces among modules that have been thus far treated as essentially monolithic, are expected to ensure inter-operation between products from different providers, and a competitive market, leading to improved quality and lower cost of ownership. In particular, Open RAN provides a richer eco-system based on the virtualization of network functions providing greater economies of scale and reduced cost. It also enables the inclusion of commodity controllers, and the ability of operators to develop their custom control applications on top of those controllers, bringing the power of software-defined networking to RANs on an open-interface basis.

Fig. 1 shows a simplified overview of the Open RAN architecture. This architecture promotes virtualized RAN, where disaggregated components are connected via open interfaces and optimized by intelligent controllers. gNodeB, which is split into a Central Unit (CU), a Distributed Unit (DU), and a Radio Unit (RU). The CU is further split into two logical components, one for the control plane and one for the user plane. This logical split allows different functionalities to be deployed at different locations of the network and on different hardware platforms. CU and DU components are called O-Cloud network functions since these can be deployed on the O-Cloud cloud layer. The management and orchestration of RAN domain is handled by the Service Management and Orchestration (SMO) system. SMO includes an intelligent component called non-Real-Time RAN Intelligent Controller (non-RT RIC). This non-RT RIC enables the onboarding of third-party applications that automate and optimize RAN operations. Several interfaces enable communication between the different components. Most are defined by the O-RAN Alliance and some by 3GPP standards. We will not go into the details of the interfaces in this paper since these interfaces are well documented in the literature [1,2].

Such disaggregation comes at the cost of increased overhead, and early Open RAN systems are widely expected to have higher overheads and lower efficiency compared to extant single-vendor systems that, after all, have evolved and been integrated for decades. Optimistic views consist of expectations of workable, if inefficient, implementations soon, followed by rapid improvements in performance. Pessimistic
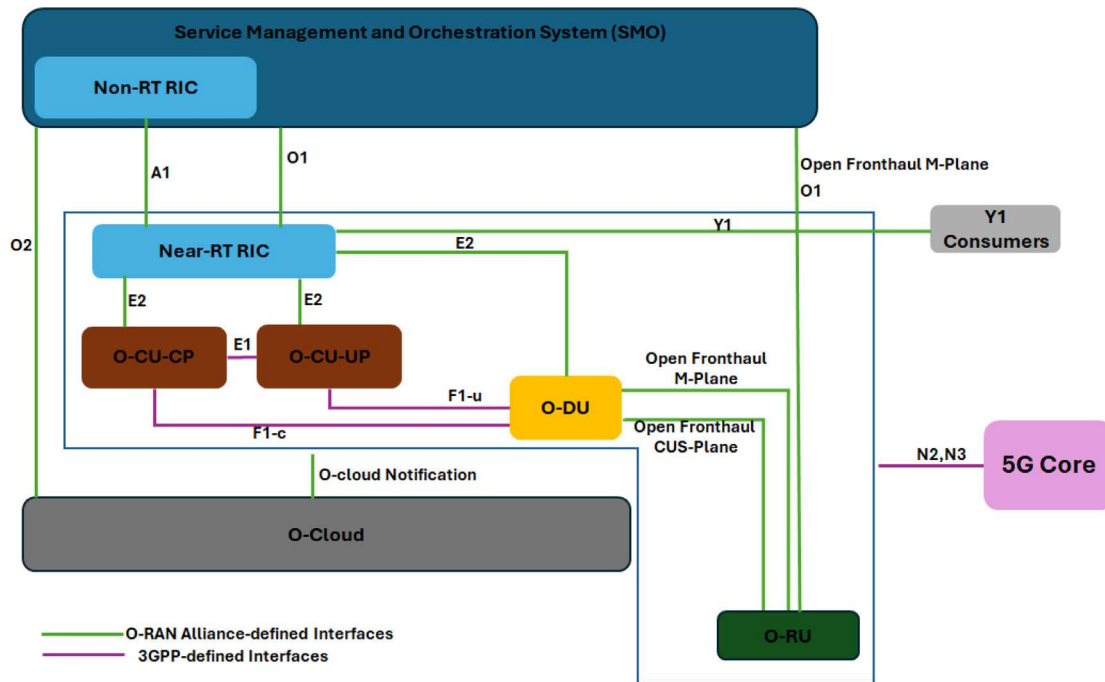
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**Fig. 1.** Open RAN Architecture (enhanced from [1,2]).

views incline to doubts regarding how long such a process might take, or whether such systems can approach the efficiency of proprietary monolithic systems, or even be workable at scale. However, there are significant gains in terms of economies of scale through virtualization as well as additional functionality that provides a much richer set of capabilities (e.g., RIC apps, etc.).

To dispassionately and pragmatically assess the workability of Open RAN, the community must move beyond early experiments and greenfield deployments to demonstrable repeatability of predictable system performance. Designing dependable test facilities for Open RAN components and systems, therefore, is among the most important outstanding tasks of the Open RAN community at this time. A key promise of Open RAN is interoperability (multi-vendor), and the key to verifying such claims is through interoperability testing (IOT). Recognizing the importance of IOT, the O-RAN Alliance has dedicated two entire work groups (WG4 and WG5) to specifying interfaces, and both groups have published specifications on interoperability testing and profiles in addition to unit test specifications (see [3,4] and other specifications of WG4 and WG5). Such profiles allow the interoperability of any set of components to be tested in test configurations that can be realized in lab-environment test benches. However, to engender the above-mentioned growing confidence, Open RAN ecosystem players (contributors, as well as vendors, operators, and users) need to be able to test components in a comprehensive E2E test facility — one that is embedded in a realistic setting and span in the real world, including at least in part an outdoor setting, with a non-trivial number of UEs interacting with a non-trivial number of base stations. In the rest of this paper, we reserve the term "testbed" to indicate facilities capable of such complete RAN system tests (we consider the distinction of such facilities from equipment testing facilities in Section 2.2).

To avoid confusion as far as possible, we largely address our remarks to the general concept of Open RAN, reserving the term "O-RAN" when speaking of the specifications proposed by the O-RAN Alliance.

### 1.2. Unpeopled aerial vehicles (UAVs)

UAVs have long been generally acknowledged as important clients of any future wide-area wireless communications system. However, the full scope of such devices as denizens of the wireless communication world is only coming to be appreciated recently. A key observation is that UAVs are not only wireless communications clients for command-and-control (the most obvious use case), but play roles in at least two other ways in the wireless ecosystem. First, trivially, as such devices increase in intelligence, and are tasked with increasingly more sophisticated missions, these missions are likely to pose additional – and likely much heavier – communication requirements; for example streaming live on-site video back to the cloud, or engaging in other data-heavy cloud-assisted distributed computation tasks. More importantly, and more significantly in the current context, with increasing on-board compute intelligence, such devices are capable of engaging not just as clients, but as crucial parts of the wireless communication infrastructure itself. This is especially important in an open interoperable ecosystem such as Open RAN aspires to be, as open competition spurs innovative contributors to explore previously unoccupied ecosystem roles.

The visioning and design exercise for an Open RAN testbed that aspires to provide interoperability and system testing capabilities, if such a facility expects to support the full evolutionary arc of aerial devices, must include reflection specific to these considerations. In this paper, we leverage our joint experience in (i) architecting and operating an advanced wireless testbed with aerial robots as primary citizens, and (ii) industry Open RAN testing and dependability expectations, to provide a starting point that we hope will be useful to such architects and designers. In the next section, we briefly review some existing test facilities with the capability (or potential near capability) of acting as Open RAN testing resources and juxtapose them with industry Open RAN testing norms, as well as basic support requirements for UAVs. In Section 3, we discuss in further detail the class of use cases that represent the potential synergistic use of UAVs in Open RAN systems. Finally, we provide a deep consideration of one extant testbed – our own NSF AERPAW platform at NC State University – to showcase the process of reviewing testbed capabilities to articulate both strengths and shortcomings in light of an ideal Open RAN testbed with native UAV support.

## 2. Visioning an open RAN/UAV testbed

### 2.1. Existing wireless testbeds and system testing

There are numerous testbeds that are accessible to researchers to experiment with wireless technologies including 5G, Open RAN, and UAVs. In Table 1, we provide a list a few of these testbed facilities that are accessible to researchers from academia, government, and industry. Note that we do not intend to present Table 1 as either comprehensive or authoritative. There are likely many facilities that we are unaware of, or for which no information is publicly available to us. Even for those we have surveyed, Table 1 represents our best knowledge as obtained from publicly available sources (as cited); we regret any unintended mischaracterization. Our survey was also heavily biased towards facilities in the USA.

Nevertheless, since our focus is on test facilities publicly or generally available to researchers and practitioners in the US, and on facilities sizeable enough for UAVs to be practically a part of the test ecosystem, we believe that Table 1 provides representative, and meaningfully extensive, information for the Open RAN testbed designer of the near future. We have chosen to characterize each facility listed by means of a few high-level considerations. Obviously, explicit currently stated support of Open RAN testing, and UAV support/integration, are features we looked for. Related to Open RAN, we also looked at the RF spectrum the facility is capable of and allowed to operate in, by noting if it lists an Innovation Zone (IZ) license from the Federal Communications Commission (see for example [5]), and also its deployment context (indoor facilities may be able to use isolation such as Faraday cages and operate without an FCC Innovation Zone or experimental licenses).

Related to UAV support, we also looked at whether such UAVs (or any component of the testbed, for those without UAVs) support controlled mobility. We consider this feature an important one for future Open RAN testbeds. A significant proportion of wireless communications system complexity arises from (or is exacerbated by) the mobility of system components, most usually that of User Equipment (UE); therefore it important for the testbed to support experiments involving mobility, hand-over, and disconnect-reconnect events. However, the core of the scientific method is the repeatability of experiments and the reproduction of experimental results. To provide this for experiments related to mobility, the relative motion of various system components must be possible to precisely reproduce on demand, for as many runs of an experiment as necessary.

Another key feature we looked for was *emulation support*. The single most valuable characteristic of actual wireless test facilities is the availability of a real Radio Frequency (RF) environment, providing real-world challenges such as fading, multi-path, and statistical uncertainty, simultaneously with the experiment repeatability. The *simulation* of RF environments by means of mathematical models, no matter how sophisticated, abstracts a measure of realism from test results; further, the experimenter has no need of an experimental facility (or even actual radios) for simulation exercises, which are an appropriate earlier stage in proving research before considering testbed validation. The exercise of *emulation*, on the other hand, provides an important added value to a testbed, in that it is a digital twin of a real RF system, capable of operating in real-time, in which physical radio equipment can actually be immersed. Emulation systems are driven by calibration (to some real RF environment) rather than modeling and may be realized by digital twinning, or more often by analog RF circuitry. In extreme cases, a test facility may be entirely based on emulation, as in the case of the Colosseum system (originally created by DARPA and currently operated at Northeastern University under NSF aegis; see Table 1). More typically, emulation support is an adjunct part of a physical test facility that can serve as an early and less costly stage of full testbed validation.

Even before moving on to discussions of testing requirements specific to Open RAN or UAVs, we can note a few points from Table 1. Naturally, those we were able to survey were largely public-use testbeds, since those are the ones that are most likely to provide information publicly about themselves. This dovetails with our focus since the interoperability focus of Open RAN implies that for engendering maximum confidence, the testbed facility should be open to anybody that is interested in repeating experiments and verifying results.

Unsurprisingly, there is no testbed on the list that provides full Open RAN as well as UAV support today, even without considering controlled mobility. Less obviously, we find that the combination of UAV support and controlled mobility is rather rare; only a handful of testbeds on our list provide even partial mobility control in conjunction with UAV support.

Interestingly, we note that a number of testbeds provide emulation support, in keeping with our expectation that this is a key required feature of wireless testbeds. However, when emulation is considered jointly with mobility control, a non-obvious consideration may be worth mentioning. For a testbed that provides mobile airborne components, any emulation system must not only emulate the physical RF environment, but also the physics of airflow and aerial navigation, including wind gusts and other disturbing factors (analogous to noise and interference in the RF environment), as well as the dynamics, features, and constraints of a specific UAV. The ability to autonomously navigate one or more UAVs in the 3D space based on RF observations in the environment is also an important capability with various use cases. Furthermore, subtle moves of the UAVs (e.g., a multicopter pitching to move forward) can change the orientation of highly directional RF antennas (especially relevant for mmWave transmissions). With this in mind, it is perhaps unsurprising that the *combination* of emulation support and mobility control is quite rare in the extant testbeds.

*Focus and Granularity of Testbed Facilities:* The facilities listed in Table 1 are largely those focused on system testing, some of which currently already support deploying some particular Open RAN system in part or in full. The focus for such facilities is often to provide a complete working system based on some Open RAN system that allows *other* things (computing applications, cyber–physical devices) to be studied in an Open RAN system. This focus is somewhat different from what is typical of industry practices, as we discuss in the next section.

Such an Open RAN testbed must include at least one complete reference Open RAN implementation, both to serve as a benchmark for other components to be tested against, and also to enable system tests to proceed for experimenters who wish to innovate in some, but not all, parts of the Open RAN ecosystem. While Open RAN provides for a multi-vendor environment in building a network from radios, vRAN software, hardware servers, and related software and services, it is important to note that "open" does not automatically or necessarily equate to "interoperable". The same need for system integration of multi-vendor Open RAN networks that has driven the need for open test environments must inform the testbed designer in choosing such reference implementations that are actually workable, and hopefully as compliant with O-RAN interface definitions as possible, so as to be broadly compatible with components and devices that testbed clients may bring in the future. In this connection, we note the attractiveness of the O-RAN Alliance's system definition as a basis for such a testbed facility.

### 2.2. Extant industry open RAN testing practices

As noted in the previous section, testbed facilities often focus on a full-system implementation of some Open RAN system (such as that provided by the O-RAN Alliance). Researchers or ecosystem developers may find this sufficient since it is possible for them to test or study their products or innovations in contiguous areas supported by "some" Open RAN implementation. However, vendors, carriers, and other ecosystem players who are involved in the business of actually building or operating a data network as a service need to focus far more deeply on component testing, and (critically for Open RAN) cross-vendor interoperability testing — especially the large swathes of new

**Table 1**

Existing testbeds with advanced wireless and UAV experimentation capabilities. Public testbeds indicated with an asterisk (*) may be open only to partners or require contacting testbed operators rather than being generally available through an experimentation portal. Features for which public information could not be found are marked as Not Known (NK). Acronyms: ES — Emulation Support, OS — O-RAN Support, US — UAV Support, CM — Controlled Mobility, FI — FCC Innovation Zone, MFA — Main Focus Area, DE — Deployment Environment, P/A: Partial.

| Testbeds (alphabetical) | Location | ES | OS | US | CM | FI | MFA | DE | Access |
|---|---|---|---|---|---|---|---|---|---|
| AERPAW [6] | Raleigh, NC | ✓ | P/A | ✓ | ✓ | ✓ | UAVs, SDRs | Rural, Urban | Public |
| ARA [7] | Central Iowa, IA | ✓ | × | × | × | × | Rural wireless | Rural | Public |
| Arena [8] | Boston, MA | ✓ | ✓ | × | × | ✓ | SDRs | Indoor grid | Public* |
| ARLIS [9] | College Park, MD | × | × | × | × | × | 5G security | Virtual | Public* |
| ARM/Tech Mahindra 5G Lab [10] | NK | NK | ✓ | × | × | × | 5G testing | NK | Private |
| Booz Allen 5G Lab [11] | Annapolis Junction, MD | NK | NK | × | × | × | Mission critical 5G | NK | Private |
| CCI xG Testbed [12] | Arlington, VA | NK | ✓ | × | × | × | SDRs, AI | Indoor | Public* |
| Colosseum [13] | Burlington, MA | ✓ | ✓ | × | × | ✓ | Emulation, SDRs | Cloud | Public |
| CORNET [14] | Blacksburg, VA | × | ✓ | × | × | × | SDRs | Indoor, Rooftop | Public |
| COSMOS [15] | Manhattan, NY | ✓ | ✓ | × | × | ✓ | mmWave, backhaul | Urban | Public |
| Drexel Grid [16] | Philadelphia, PA | ✓ | × | × | × | × | Emulation, SDRs | Indoor grid | Public* |
| Ericsson Open Lab [17] | NK | ✓ | ✓ | × | × | × | CloudRAN, virtualized 5G | Indoor | Private |
| INL Wireless Testbed [18] | Idaho Falls, ID | × | × | ✓ | P/A | × | Wireless security | Rural | Private |
| IRIS [19] | Los Angeles, CA | × | × | × | ✓ | × | Robotic wireless networks | Indoor | Public* |
| LinQuest Labs [20] | Chantilly, VA | ✓ | NK | ✓ | NK | × | 5G security, UAV, NTN | Cloud, indoor | Public* |
| NASA MTBs [21] | × | × | × | × | ✓ | × | Multirotor UAV testing | Indoor | Public* |
| New York UAS Test Site [22] | Rome, NY | × | × | ✓ | P/A | × | BVLOS UAV testing | Rural, Urban | Public* |
| NIST 5G Coexistence Testbed [23] | Boulder, CO | ✓ | NK | × | × | × | 5G coexistence testing | Indoor | Public* |
| NIST NBIT Testbed [24] | NK | × | | × | × | × | Spectrum sharing | Indoor | Public* |
| NITOS [25] | Volos, Greece | × | ✓ | × | × | × | Cloud-based Wireless services | Rooftop | Public |
| Northeastern UAS Chamber [26] | Burlington, MA | × | × | ✓ | NK | × | Drone flights | Drone cage, anechoic chamber | Public* |
| ORBIT [27] | N. Brunswick, NJ | ✓ | × | × | × | × | SDRs | Indoor grid | Public |
| PNNL 5G Innovation Studio [28] | Richland, WA | × | × | × | × | × | Commercial 5G | Indoor | Private |
| POWDER-RENEW [29] | Salt Lake City, UT | ✓ | ✓ | × | × | ✓ | SDRs, massive MIMO | Urban | Public |
| RELLIS 5G testbed [30] | Bryan, TX | × | NK | NK | NK | | 5G (AT&T) | Outdoor | Public* |
| Cyber Living Innovation Lab [31] | Fairfax, VA | NK | ✓ | NK | NK | × | 5G security, robotics | Indoor | Public* |
| SOAR [32] | Buffalo, NY | × | × | ✓ | P/A | × | Drone flights | Drone cage | Public* |
| TIP Community Lab [33] | Overland Park, Kansas | NK | ✓ | × | × | × | O-RAN 5G NR (Sprint) | NK | Private |
| UNH Interoperability Lab [34] | Durham, NH | × | ✓ | × | × | × | Interoperability testing | Indoor | Public* |
| Virginia Tech Drone Park [35] | Blacksburg, VA | × | × | ✓ | P/A | × | Drone flights | Drone cage | Public* |

interoperability modes enabled by Open RAN's disaggregation modes. The focus is now on testing the compliance and interoperability of various system components of Open RAN, rather than studying the behavior of other things in the Open RAN ecosystem.

We note O-RAN Alliance's effort towards this direction by certifying Open Testing and Integration Centers (OTICs), as summarized in Table 2, and establishing O-RAN Certification and Badging Program [56] which is focused on ensuring conformance, interoperability, and/or end-to-end (E2E) testing of O-RAN products and solutions. Detailed definition of these have been provided by the O-RAN Alliance; briefly, *Certification* refers to compliance testing of any specific O-RAN system component, including its interfaces, whereas *Badging* refers to verification of a combination of units (typically from disparate providers) to interoperate correctly.

Such testing proceeds by identifying Key Performance Indicators (KPIs) of interest, and then measuring them for Devices Under Test (DUT) or System Under Test (SUT) for comparison purposes, as well as possible absolute acceptance criteria. It would seem a reasonable expectation that an Open RAN system testbed should enable such KPIs to be measured, not just E2E, but at interoperation points or interfaces (and for specific O-RAN alliance defined interfaces, including F1/W1/E1/X2/Xn).

**Table 2**

Existing O-RAN Testing and Integration Centers (OTICs) [36]. Acronyms: TS — Testing Services, CTF — Certification, IOTB — Interoperability Badging, E2EB — End-to-end Badging, ST — Security Testing, A&P: Asia-Pacific, EU: European, NA: North American. OTICs are listed alphabetically.

| OTIC Name | Location | TS | CTF | IOTB | E2EB | ST | Other |
|---|---|---|---|---|---|---|---|
| A&P OTIC by ritt7layers [37] | Suzhou City, China | ✓ | × | × | × | × | Troubleshooting/debugging, data analytics, Engineering Consultancy |
| A&P OTIC in PRC [38] | Beijing, China | ✓ | ✓ | ✓ | ✓ | × | Testing professional services, troubleshooting, data analytics, and consulting |
| A&P OTIC in Singapore [39] | Singapore | × | × | × | × | × | NK |
| Auray OTIC and Security lab [40] | Taiwan | ✓ | ✓ | ✓ | ✓ | ✓ | Results interpretation, troubleshooting, root cause analysis, and O-RAN consultancy services |
| EU OTIC in Berlin [41] | Berlin | ✓ | ✓ | NK | NK | ✓ | Results interpretation, troubleshooting, root cause analysis and consultancy services |
| EU OTIC in Madrid [42] | Madrid | NK | NK | NK | NK | NK | NK |
| EU OTIC in Paris [43] | Paris | ✓ | NK | NK | NK | NK | Integration of the product in the testbed, definition of the test specifications, debug, analysis of the results |
| EU OTIC in Torino [44] | Torino, Italy | ✓ | × | × | × | ✓ | Expert support, debug tracing for IOT troubleshooting and test list and report preparation |
| Japan OTIC [45] | Japan | ✓ | ✓ | ✓ | ✓ | × | NK |
| Korea OTIC [46] | Republic of Korea | ✓ | ✓ | NK | NK | NK | NK |
| Kyrio O-RAN Test and Integration Lab [47] | CO, USA | ✓ | ✓ | ✓ | ✓ | × | Provides device manufacturers with automated, remote, and flexible test capabilities for the full product development lifecycle |
| NA OTIC in the Raleigh-Durham Research Triangle Park Area (AERPAW) [48] | NC, USA | × | × | × | × | × | Results interpretation, testing and integration expertise |
| NA OTIC in the Boston Area (Northeastern University) [49] | MA, USA | ✓ | NK | NK | NK | ✓ | NK |
| NA OTIC in the Boston Area (UNH-IOL) [50] | NH, USA | NK | NK | NK | NK | NK | PlugFest |
| NA OTIC in Central Iowa (ARA) [51] | IA, USA | ✓ | × | × | × | × | NK |
| NA OTIC at MITRE [52] | MA, USA | NK | NK | NK | NK | NK | NK |
| NA OTIC in NYC Metro Area/East (COSMOS) [53] | NJ, USA | ✓ | NK | NK | NK | NK | Speaker sessions, tutorials, and workshops |
| NA OTIC in Salt Lake City (POWDER) [54] | UT, USA | ✓ | ✓ | ✓ | ✓ | × | On-demand, orchestrated and automated O-RAN related testing and development services, general O-RAN lab-as-a-service capabilities |
| NA OTIC in Washington DC/ Arlington VA (Virginia Tech) [55] | VA, USA | ✓ | NK | NK | NK | NK | Sandbox for O-RAN R&D and innovation |

However, once one enters the domain of detailed KPIs, there is little standardization of what to measure. To an extent, the detailed definition of KPIs is part of the specialized knowledge of vendors, operators, and testing service providers that are perceived to provide a competitive advantage, and hence considered confidential. Because many of the KPIs may be specific to specific vendors, there are also a very large number of them. Commercial 5G networks test and validate literally thousands of KPIs; the testing regime of well-known mobile operators actually includes over ten thousand KPIs. Many KPIs have sub-KPIs and the RF optimization KPIs are substantial. This will only increase further with the greater use of disaggregation in Open RAN networks. There are numerous Open RAN interoperability and validation labs today. There are private and public testbeds supported by vendors, consortia, universities, and the government. Not all labs concentrate on all parts of the toolchain and ecosystem, most focus on specific aspects; validation testing will be greatly dependent on the use case and focus of the lab. In the Open RAN ecosystem, the RAN Intelligent Controllers (RICs) allow for x-Apps and r-Apps to use the RIC framework as an engine, but with custom functionality. This implies that every such app can be expected to have a fairly large number of KPIs associated with it depending on its particular functionality. There is the potential for cross-KPIs between the different apps as well.

In light of this, we are forced to go back to fundamentals in recommending KPI capabilities for Open RAN testbeds. At the highest level of abstraction, there are certain priority KPIs that are foundational for a validation environment, and detailed consideration of many custom KPIs for various operators and vendors (although we are not in a position to list them here) can be seen to trace back to one or the other of these few foundational KPIs:

- Ability for UE to attach to the network;
- UE link quality — uplink and downlink;
- UE throughput — uplink and downlink;
- Latency;
- Retainability;
- Accessibility; and
- Optimization.

Each of these KPIs drives multiple other test parameters and features such as performance, load testing, and RF design and optimization. At this time, practical Open RAN testing in the real world is largely confined to component testing and using KPIs related to the top few items in the above list; in the future, more testing related to the Accessibility and Optimization KPIs is likely to proceed.

**Table 3**

Example components for an Open RAN validation environment testbed.

| Open RAN Components | Test/Evaluation Components |
|---|---|
| • 5G core access and/or edge | • A Faraday cage/environment |
| • Open RAN Radios: gNB/eNB (some at controllable UAVs) | • 5G signal analyzer – test and validate measurements |
| • vRAN SW | • RTSA: Real-time spectrum analyzer |
| • GPS system(s)/Antenna- for synchronization | • Network analyzer- antenna system and cable measurements |
| • Forward Error Correction (FEC) | • Antenna testing: anechoic chamber- measure patterns |
| • Edge /Server, part of the core network in a box | • Smaller Shielded enclosures, Faraday cages for individual UAV testing |
| • (Open) RIC platform | • Traffic generator |
| • rApps, xApps | • Interferers – for testing purposes |
| • UEs (some at controllable UAV for certain use cases) | • Various Adapters: need for every type of connector |
| • ToR switch | • Jumper cables |
| • Cell site routers (CSR) | • Attenuators |
| • Acceleration for Open RAN | • Power splitters/power dividers |

In Table 3 we have summarized what we perceive to be key high-level components for an Open RAN validation environment testbed.

### 2.3. Supporting UAVs in a testbed

In its simplest form, any aerial robot (i.e. an airborne device that stays aloft for significant periods of time and is capable of directed motion) can be considered a UAV, but the term is usually reserved for devices that are capable of full (or at least a high degree of) autonomous operation. A UAV can therefore exhibit not only primitive autonomous behavior (pre-programmed/way-point trajectory, heat-seeking, collision avoidance, auto-return-to-launch on predetermined conditions such as GPS-lock-loss), but also more complex operations such as computed conditional sensor-driven on-the-fly trajectory control (such as search-and-rescue), participation in coordinated trajectory control locally (platoon or swarm behavior) or globally (such as UTM – the US Federal Aviation Authority's Unmanned Aircraft System Traffic Management – or similar), or dynamic self-aware re-tasking (such as degrading mission parameters for safety if battery reserves fall to risky levels).

In distinguishing between testbed support of UAVs, it is important to realize that a UAV implies close integration of the onboard computing and communication equipment with the vehicle's command and control. It is helpful to think of two extreme cases as representative of the two classes. On the one hand, we can mount a computing/communication device (such as an ordinary smartphone) on a UAV. The UAV's autonomy, trajectory computation, or command and control, remain completely as before. The coupling between the UAV and the cellphone it carries as a payload is simply mechanical (but may include antenna mounts or high-gain antennas custom-positioned for the UAV, and common power supply). At the other extreme, the UAV contains only a single computing/communication device, which is capable of being tasked with complex missions (such as air quality analysis, image analysis based search-and-rescue), and also subsumes the trajectory computation (whether autonomous, command-and-control-based, or based on some coordination) for the UAV; in this case, the vehicle becomes in effect a peripheral of the onboard computer.

First, we consider the task of integrating support in a wireless testbed for UAVs only, used as vehicles for an airborne UE. This includes the case where the air vehicle has no autonomy and is controlled by a ground-based operator using a handheld or other radio remote control equipment; and even the case where the air vehicle does not have any controlled mobility (such as free-floating balloons) or any mobility at all (such as tethered aerostats or helikites). The basic challenge for a wireless testbed to support UAVs is posed not only by
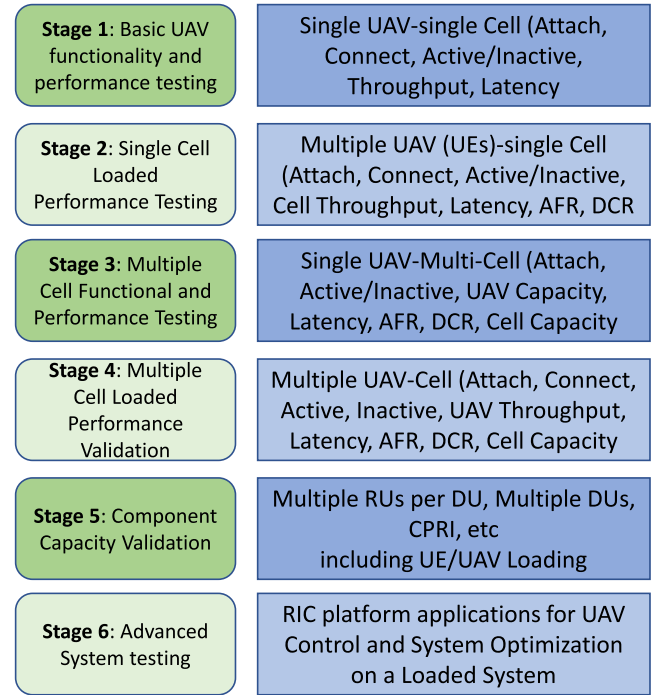


**Fig. 2.** Proposed stages for Open RAN UAV validation.

the fact that they are mobile (which, after all, ground UEs also exhibit, when users walk or drive), but the fact that they have a widely varied altitude as well as azimuth compared to traditional UEs on the ground. Both spectrum and latency are KPIs of interest for a UE. The front-haul and mid-haul latencies must provide very low latency to maintain system synchronization and function under a varying altitude of the UE, and the spectrum used for communication can significantly affect the achievable coverage and throughput. A further challenge is that of antenna occlusion, which some UAVs attempt to mitigate by multiple antenna locations around their bodies. Some UAVs mount antennas on gimbals in an effort to maintain constant directional properties, others allow for servos to allow controlled pointing of antennas. These challenges are exacerbated by the fact that most base stations, whether commercial or built out of commodity open technology, exhibit their own antenna coverage patterns, which are optimized for ground coverage. Studies have shown that the consequence of this optimization is the formation of multiple lobes at increasing altitudes, in complex patterns, that cannot be predicted easily as a function of the altitude of the UAV.

The UAV will have to be tested in a controlled environment to ensure the network functions meet radio and RAN specifications. Creating a Faraday environment to do the controlled validation testing will pose challenges compared to traditional Open RAN lab Faraday environments. Then the testing will need to be expanded to an open environment and optimized based on interferers, physical obstacles, and spectrum bands used — as the propagation and throughput are connected to the spectrum band used for communications. In Fig. 2, we summarize six proposed stages for Open RAN UAV validation.

While UAVs allow intelligent control of position and trajectory jointly with RAN intelligence (Apps executing at the RICs), the softwarized character of Open RAN also opens up exciting possibilities of allowing the onboard computer to take part in the Open RAN ecosystem in ways other than just as a UE. We devote the next section to these considerations.
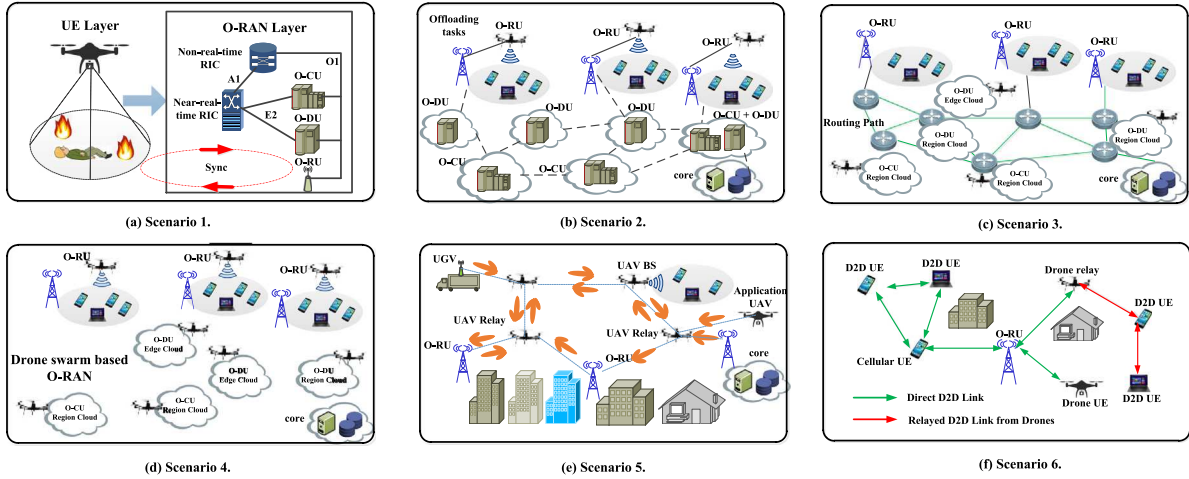
**Fig. 3.** Use case examples for Open RAN-based air mobility: (a) UAVs as UEs; (b) UAVs as O-RUs; (c) UAVs as O-DUs and O-CUs; (d) UAV swarms in Open RAN; (e) Flying wireless backhaul in Open RAN; (f) D2D communications underlaying UAV-assisted Open RAN.

## 3. Use cases for UAVs in open RAN

Considering the aerial controlled mobility and communication among fixed and portable nodes, UAVs will facilitate enhancements to Open RAN with flexible deployments and on-demand, on-time network access. We foresee several use case examples on Open RAN-based air mobility scenarios as follows (see Fig. 3). (Subsequently, we position the UAV usecases specified by the O-RAN Alliance with respect to these scenarios.)

*Scenario 1. UAVs serve as UEs*: This use case focuses on exploring the functionalities of Open RAN RICs for managing and orchestrating network components aimed at 3D critical mission operations (e.g., secure, search and rescue) assisted by UAVs, as they are able to exhibit agile, fast, and autonomous behavior by organizing themselves to exchange information. Considering a scenario involving UAVs connected to an Open RAN ground BS, UAVs as UEs can carry high-resolution cameras and/or sensors, collecting real-time video and transmitting it back to the ground BS, e.g., to be used to identify possible targets of interest through deep neural network object detection model, and in addition report information about application performance to *rApps*. In the meantime, the E2 nodes of Open RAN are responsible for updating UAV control with insights produced by their applications (*xApps* and *rApps*) to support the RAN optimization process. In this context, Open RAN is able to support the demands of highly dynamic scenarios of critical-mission operations integrated with UAVs due to its flexibility and characteristics of component dissociation.

*Scenario 2. UAVs act as O-RUs*: As described in Open RAN specifications [57,58], UAVs can play a role as O-RUs and process several simple tasks. As the extension, this scenario focuses on the use of UAVs as O-RUs to handle more complicated network tasks, e.g., to quickly deploy an aerial network to assist or extend the terrestrial network where communication and computing resources can move closer to users to meet diverse and stringent 5G application requirements, such as ultra-low latency and ultra-high reliable connectivity. Considering a scenario in which each UAV-BS is equipped with an O-RU to serve ground mobile users, the objective is to optimize the performance of serving offloading tasks via both controlling UAV-BSs to guarantee the quality of communication channels to ground users and efficiently distributing offloading tasks to appropriate Open RAN elements according to the current association. Because of the 3D air mobility capability of UAVs and disaggregation of Open RAN architecture, they may potentially deliver better data offloading capabilities and better resource utilization.

*Scenario 3. UAVs act as O-DUs and O-CUs*: (1) Using UAVs as O-DUs allows for flexibly hosting RLC/MAC/High-PHY layers based on

a lower layer functional split, where UAVs can dynamically connect to multiple O-RUs allowing on-demand resource pooling for virtual baseband functions of high PHY layer, MAC, RLC, and synchronization; (2) using UAVs as O-CUs helps to easily control the operation of multiple O-DUs within/beyond the coverage area, e.g., the radio resource control for flexibly managing the life cycle of the connection, routing or duplication for split bearers, and the service data adaptation for managing the QoS of the traffic flows through autonomous 3D air mobility capability of UAVs.

*Scenario 4. Drone swarm based Open RAN*: This use case envisions multi-role drones without ground facilities that forms an ad-hoc/swarm based Open RAN. Based on *Scenarios 2–3*, we can consider a set of containers to virtualize different Open RAN elements such as O-RUs, O-DUs, and O-CUs deployed in drones and distributed computing nodes of the network. Given these containers with different functions, the objective is to create a robust Open RAN testbed in a swarm of drones towards full decentralization and controlled air mobility.

*Scenario 5. Flying wireless backhaul in Open RAN*: Wireless backhaul as an economically sustainable solution has been included by 3GPP as part of the integrated access and backhaul study item [59,60] for the 5G NR standard. As an extension in Open RAN architecture, this scenario focuses on building a large-scale, self-organizing network of drones that are connected using a wireless mesh backhaul, which caters to dynamic bandwidth-hungry and latency-sensitive applications. Based on *Scenario 4* with role-specific operations, drones can hover above or close to the O-RU and serve as an airborne last-hop link connecting RAN to the core network. Additionally, they can act as relays between two O-RUs separated by a longer distance to extend coverage forming a multi-hop mesh network for communications and control. Multi-drone backhaul in Open RAN is capable of flexibly adapting itself to cater to highly dynamic applications and events, and easily being scaled up to cover urban scenarios using long-range radios.

*Scenario 6. D2D communications underlaying drone-assisted Open RAN*: Implementation of device-to-device (D2D) communication such as sidelink can be an extension of the network into areas that traditional propagation of the fixed O-RU cannot reach. Particularly, drones can serve as UEs or relays deployed much more swiftly and improve the network throughput performance by dynamically adjusting their locations to provide direct or relayed D2D links to any out-of-coverage users. Additional sidelink capabilities such as multi-hop [61] and multi-link (in 3GPP Rel. 19) can provide higher resiliency in this mode, especially offering a valuable set of capabilities for mission-critical services such as disaster response rescue and operation.

*UAV use cases in O-RAN Alliance*: There are two UAV use cases specifically highlighted in an O-RAN Alliance White Paper [58], both
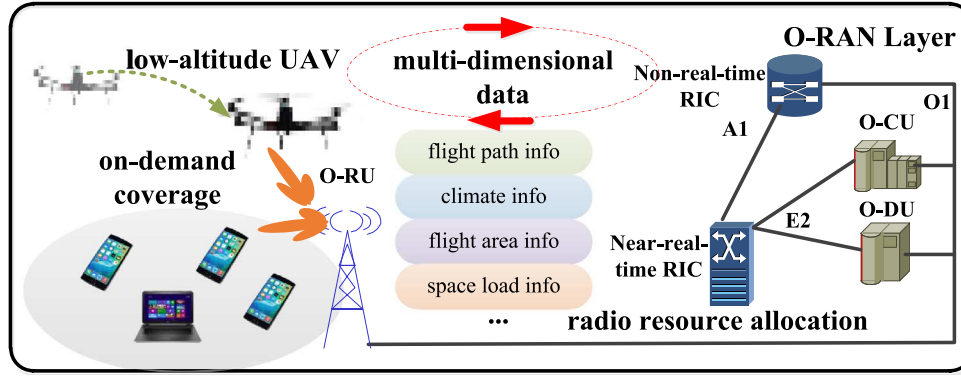
**Fig. 4.** Use case for dynamic UAV resource allocation.

of which align with our Scenario 1 listed above. The first use case involves dynamic UAV resource allocation based on flight paths, facilitated by 5G for high-speed data transmission for low-altitude UAVs, replacing traditional communication links. However, challenges arise in areas with ground cover construction, causing potential disconnection issues due to interference and lack of coverage cells. In Open RAN architecture, multi-dimensional data (including UAV metrics and flight information) is acquired for AI/ML model training. Near-RT RIC can allocate radio resources based on channel conditions, flight paths, and application data, addressing on-demand coverage for UAVs, as illustrated in Fig. 4. In the second use case that considers a *UAV Control Vehicle* scenario, the Open RAN architecture addresses wireless resource adjustment requirements. This scenario entails Rotor UAVs flying at low altitude, equipped with cameras or sensors, similar to Scenario 1 depicted in Fig. 3(a). Operating in the 5.8 GHz range, the UAVs perform tasks like border/forest inspection, base station checks, field mapping, pollution sampling, and HD live broadcast. UAV mobile control stations and anti-UAV weapons collaborate to counter illegal UAVs, ensuring low-altitude safety in specific areas.

The *UAV Control Vehicle* deploys Non-RT RIC, Near-RT RIC, O-CU, O-DU, and application servers. It synchronizes with the UE layer data, including 4 K high-definition video, exhibiting uplink and downlink service asymmetry, with the Near-RT RIC managing radio resources for O-CU and O-DU sides.

*Testbed Considerations*: The above poses a rich and variegated set of potential operational scenarios, and it is impractical to attempt to enumerate specific design issues. Instead, we again propose foundational considerations and hark back to our discussion in Section 2.1. The general capabilities of the testbed that we can identify in order to support such innovative scenarios are:

- The capability of mobility control of custom air vehicles,
- The ability to emulate not only the RF environment, but of airflow and UAV flight, and
- The inclusion of onboard computers, suitable for integration into UAVs, that can support user programming to create software components of the Open RAN ecosystem.

## 4. AERPAW testbed review for open RAN

Thus far, we have reflected on general requirements of an Open RAN testbed that is able to integrate UAVs with controlled mobility. In the remainder of this paper, we take a deep dive into the AERPAW testbed, reviewing it in light of the considerations we have derived above. We choose AERPAW because we are intimately familiar with it; the authors of this paper include the PIs of the AERPAW project, and key architects and DevOps personnel working on the AERPAW facility. However, it is also true that AERPAW was conceived and built to support controlled air mobility in a testbed for use by a national community of researchers.

Thus, it is a reasonable facility in which to conduct such a thought exercise of how a fully-featured Open RAN testbed may be built up along the same lines. AERPAW has the foundation for becoming a highly valuable Open RAN UAS test-bed. For readers unfamiliar with AERPAW, we briefly describe it in the next four paragraphs.

AERPAW is the third testbed funded under the PAWR initiative to support advanced and emerging wireless research. It is a multi-year, multi-phase project that started in September 2019 and it is expected to be finalized by 2025. AERPAW experimentation capabilities became generally available with an initial set of resources and features in November 2021. Additional platform resources, sample experiments, and experimentation capabilities are expected to be released at the end of Phase-2 (in January 2024) and Phase-3 (by early 2025). AERPAW is primarily and essentially a testbed of physical resources, not computing resources. The crucial part of these physical resources are: (i) the RF environment and the airspace that the AERPAW operating areas represent; (ii) the physical equipment (SDRs, commercial RF equipment, UAVs, and UGVs) that AERPAW provides to leverage those environments for experimental studies; and (iii) the expertise (and consequent 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 that can be placed under the direct programmatic control (of trajectories) of the researcher. 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 a number of tower locations (fixed nodes), at each of which some combination of AERPAW programmable SDRs and commercial radio equipment are permanently installed. The SDRs are controlled by servers, or companion computer (CCs), installed in each location that also represents edge-computing capabilities. These fixed node locations are distributed over the extensive Lake Wheeler Agricultural Fields of NC State (see Fig. 5(a)), and some nodes are also installed in the Centennial Campus (see Fig. 5(b)). 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 and User Manual linked therefrom, and previous publications (also listed on the website). In what follows, we attempt not a comprehensive overview of AERPAW, but rather a review in light of the desirable characteristics we identified above.
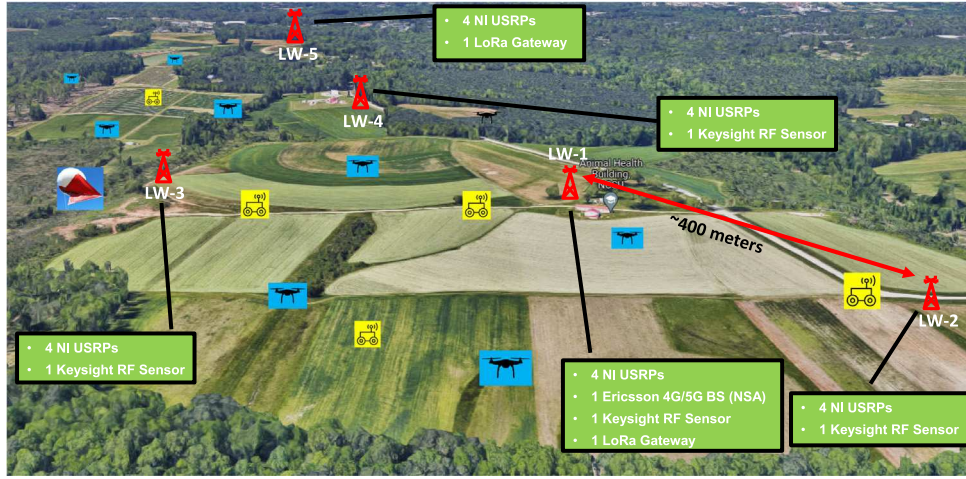
(a) Since November 2021, LW-1 is publicly available for experimentation, and LW-2, LW-3, LW-4, LW5 have been publicly available since February 2024.
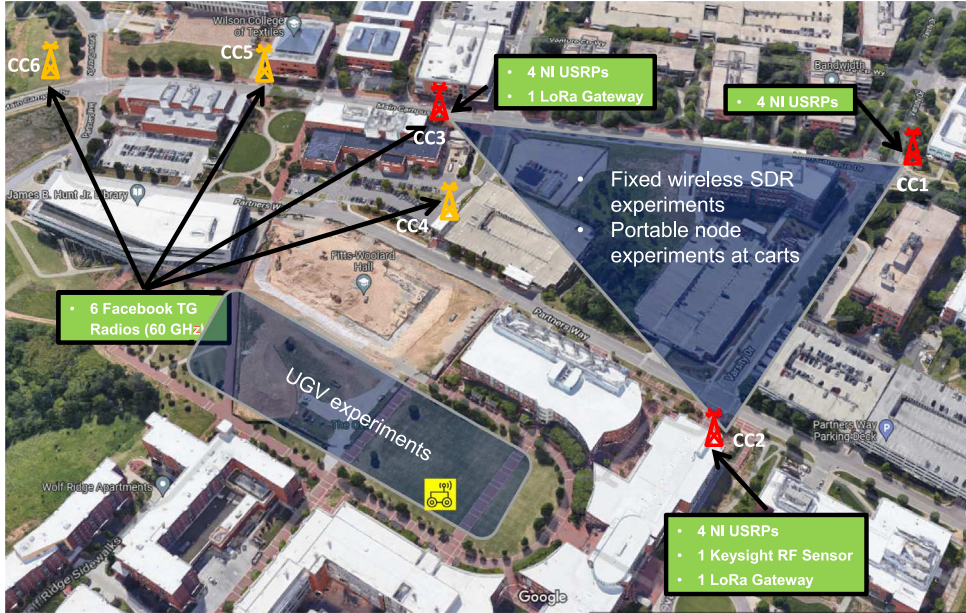


(b) Since Nov. 2022, CC1, CC2, CC3 have been publicly available for experimentation. CC3, CC4, CC5, and CC6 each have Terragraph radios from Meta operating at 60 GHz.

**Fig. 5.** AERPAW fixed node deployments at (a) NC State University Lake Wheeler Field Labs, Raleigh, NC; and (b) NC State University Centennial Campus, Raleigh, NC.

## 4.1. Span, scale, access

Figs. 5(a) and 5(b) show the outdoor deployment footprint of AER-PAW's fixed nodes in NC State Lake Wheeler and NC State Centennial Campus, respectively. The equipment that are expected to be available publicly for experimentation by the end of AERPAW's Phase-2 (expected in January 2024) are also illustrated. Currently, it is possible to experiment with UAVs at Lake Wheeler Field Labs; AERPAW does not currently support UAV operation by experimenters in Centennial Campus but supports UGV operation, and UAV operation will likely become available in the future for experimenters.

This geographical span is reasonable for an Open RAN testbed, even with experiments including UAVs. However, scale is a different matter. With nine fixed nodes, six portable nodes, eight programmable UAVs, and some non-programmable commercial radio systems such as an Ericsson base station and five Keysight RF sensors, AERPAW can support a large variety of meaningful advanced wireless research — including proof-of-concept Open RAN experiments at small scales. But to support the full gamut of Open RAN testing and Open RAN

related research experiments, AERPAW would need to add a large number and variety of commercial or stock UEs, and a larger number of programmable UAVs; a few more programmable fixed and portable nodes would also likely be useful.

In Open RAN, the potential softwarization or virtualization of various system components is a particularly attractive feature for innovators. This requires allowing experimenters direct programming access to all parts of the facility and at the highest levels of access. Managing such access while ensuring the safety and regulatory compliance of the facility is a distinct challenge for any testbed that aspires to achieve this.

On this front, AERPAW is already well positioned, having been designed from the outset as a *batch-mode facility* with emulation and physical environment. As detailed in our other paper [62], the emulation environment is a custom software-based virtual environment that simulates, predicts, and optimizes the performance of its physical counterpart. It uses environment emulators, as shown in Fig. 6, where actual AV, radio, and other (e.g., vision) software interact with each other through the environment emulator, therefore capturing the complex
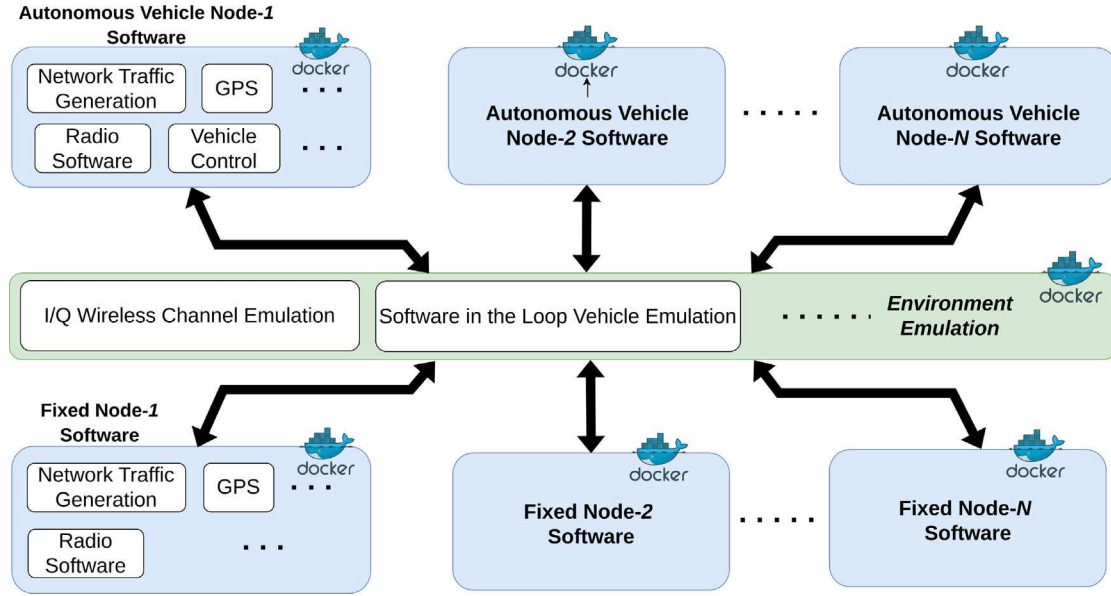
**Fig. 6.** Experiment Emulation Components.

protocol, radio, and vehicle control interactions in the AVN. Experimenters develop experiments in the emulation environment and submit experiments for execution on the physical testbed once development is complete. AERPAW Operations personnel (Ops) then execute these submitted experiments in the physical testbed environment and collect the output of the experiments as designed by the Experimenters, which are available for Experimenters to view and analyze back in the virtual environment.

This is not an arbitrarily decided constraint, but a considered architectural choice. In operating a facility with programmable radios and programmable air vehicles, we are obligated to make, and uphold, certain guarantees to the FCC and FAA. However, we also want to allow Experimenters the ability to program those radios and air vehicles, ideally without needing to become fully conversant with FCC and FAA regulation details, obtain exemptions, or expertise in techniques for ensuring compliance. Batch mode operation allows us to interpose critical filters and monitors into the Experiment code execution flow that allow us to guarantee safe and compliant operation. It is one of the most valuable features of the AERPAW platform that we assume this guarantee ourselves, rather than passing on the responsibility for compliant operations (and liability for non-compliance) to the Experimenter.

Fig. 7(a) and 7(b) show the entity relationships in AERPAW, and the experimenter's experiment design workflow. Experimenters request "Development Sessions" in which they program a virtual environment that is programmatically indistinguishable from the computing environment in the physical testbed. Once completed, they submit such experiments for "Testbed Execution Sessions". The containers housing the experimenter's code is bodily moved to the corresponding nodes in the physical testbed, where they are executed as before, but with additional supervisory containers monitoring for any RF violation or unsafe air-vehicle operating conditions, overriding as necessary. As an additional line of defense, human operators in the field are able to issue aborts if the automated system should fail to override.

### 4.2. Spectrum and licenses

AERPAW supports multiple frequencies for experimentation with its fixed and portable nodes and vehicles. In particular, AERPAW is one of the few FCC Innovation Zones (FCC-IZs) in the United States [63, §1.6] with frequency bands that are highlighted in Table 4. The maximum effective isotropically radiated power (EIRP) limits for fixed stations (FSs) and mobile stations (MSs) are also specified in the table. The

FCC-IZ for Lake Wheeler Field Labs site for AERPAW covers an area of approximately 10.5 square miles, while the Centennial Campus FCC-IZ covers an area of approximately 3 square miles. Experimenters can also port their FCC experimental licenses at AERPAW's FCC Innovation Zone. As noted in Table 4, due to the sensitivities of certain bands and the wide interference footprint of transmissions from an aerial vehicle, FCC does not allow airborne use in certain bands [64].

AERPAW currently supports a subset of the frequency bands through additional FCC experimental licenses (FCC Call Sign: WK2XQH [65]), which are offered to AERPAW's users to carry out over-the-air experiments on the platform. In particular, for SDR experiments, AERPAW has experimental licenses at 3.3–3.55 GHz and 902–928 MHz, while AERPAW is exploring with the FCC to add these frequency bands into its FCC-IZ. Additional frequency bands that AERPAW is exploring to add to its FCC Innovation Zone include 482–488 MHz, 2025–2110 MHz, 5030–5091 MHz, 24–30 GHz, and 122.5–140 GHz. The experimental licenses for the Ericsson network include 1.7/2.1 GHz for the LTE system and 3.4 GHz for the 5G system. AERPAW also has plans to support generally available experiments using its mmWave SDR framework using Sivers phased arrays operating at 28 GHz. Spectrum monitoring and passive I/Q data collection experiments can be supported using USRPs and Keysight RF sensors between 100 MHz to 6 GHz.

An important spectrum band that is of recent interest to safety and navigation related command-and-control communications for UAVs, and that AERPAW will explore experimental licenses in the future, is 5030–5091 MHz for which FCC recently released a Notice of Proposed Rule Making (NPRM) [66]. Another band that may potentially be used for ensuring vehicle-to-vehicle (V2V) separation with cooperative surveillance in the future for urban air mobility (UAM) scenarios is 1104 MHz (also known as UAT2) [67–69]. Additional spectrum bands that are specifically of interest for UAV/UAM scenarios can be found in [64].

### 4.3. Mobility control

AERPAW is also, by its original design, already adequate in providing controlled mobility, both for repeatability of experiments and for experimentation with programmatic trajectory control by experimenters; and both for aerial vehicles as well as ground vehicles. Fig. 8 shows the AERPAW vehicle control stack. In AERPAW the main autopilot we support at this time is ArduPilot [70] as it is open source
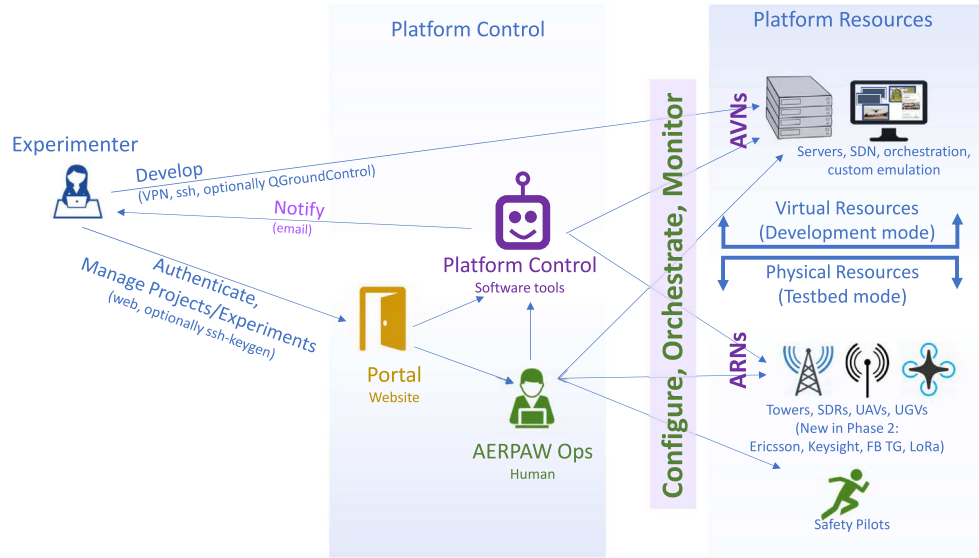
(a) Interaction of an AERPAW experimenter with platform control and platform resources (development mode and testbed mode).
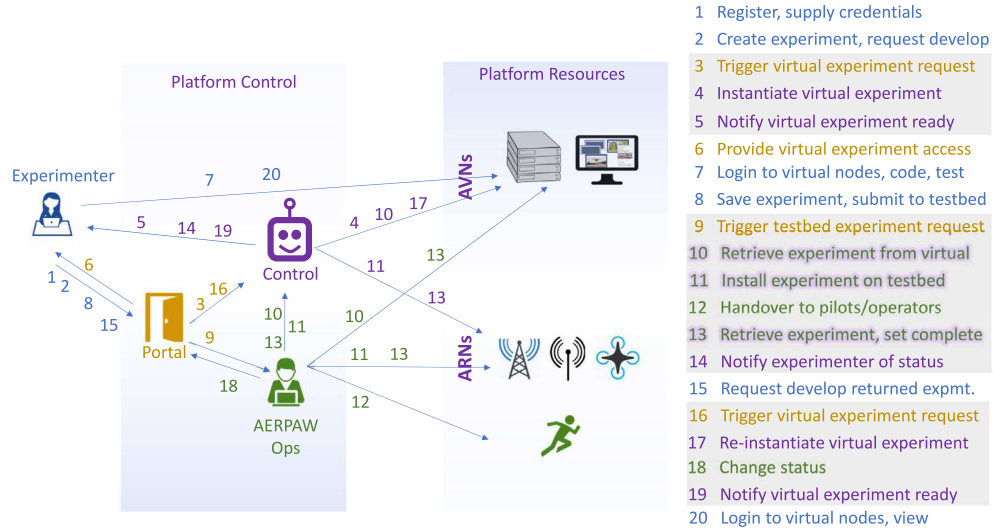


(b) Steps for carrying out an experiment in AERPAW..

**Fig. 7.** Experiment workflow for users of AERPAW.

and well-trusted. ArduPilot is supporting MAVLink [71] as a communication protocol, and, therefore, all AERPAW vehicle software sends and receives MAVLink commands. For the safety of the testbed and of the AERPAW operators, only a reduced subset of MAVLink commands is allowed to pass through the MAVLink Filter and reach the autopilot.

Keeping in mind the caveat on the reduced subset of MAVLink commands allowed passing to the autopilot, at one extreme, an experienced AERPAW user can, however, discard the entire stack shown at the top of Fig. 8 and write their own MAVLink application using any other framework they wish (e.g., they could use MAVSDK [72] if they prefer a C++ based library).

However, to smooth the learning curve, we implemented a vehicle library named aerpawlib [73], which features a finite state machine model, with hooks for vehicle (and/or radio) actions at each state. Several examples are available either to be used as-is or to be modified by experimenters to fit their needs. The most popular example at the moment is the predetermined trajectory sample application, where users specify a series of 3D waypoints to be traversed in order, including choices of the speed and wait times at each waypoint.

The AERPAW framework also allows the experimenter's programs to take decisions on the fly, thus enabling autonomous applications, such as a radio-based search and rescue (SAR), where the next direction of movement can be chosen based on the current radio measurements.

*Autonomous Coordinated Multi-UAV Experiments:* An additional feature supported by the application programming library provided by AERPAW is the ability of applications to synchronize the control of multiple vehicles. This is achieved either by using centralized control (where a coordinator program sends synchronized commands to multiple vehicles), or decentralized applications, (where programs on the companion computer of each of the vehicles coordinate without a centralized conductor). This ability can be leveraged to allow for swarm control. Fig. 9 shows the traces followed by two drones in a coordinated drone experiment, where one drone (the tracer) follows a list of waypoints, while the second drone (the orbiter) shadows the tracer by moving at the same time in the same direction, and upon reaching the target waypoint, it orbits around the tracer once before they both move to the next waypoint.

This experiment is initially designed and tested in the emulation environment and subsequently executed in the testbed environment.

**Table 4**
AERPAW's FCC-IZ frequencies.

| Frequency Band | Type of Operation | Allocation | FS Max EIRP | MS Max EIRP |
|---|---|---|---|---|
| 617–634.5 MHz (DL) | Fixed | Non-federal | 65 | – |
| 663–698 MHz (UL) | Mobile | Non-federal | – | 20 (dBm) |
| 907.5–912.5 MHz | Fixed and Mobile | Shared | 65 (dBm) | 20 (dBm) |
| 1755–1760 MHz (UL) | Mobile | Shared | – | 20 (dBm) |
| 2155–2160 MHz (DL) | Fixed | Non-federal | 65 (dBm) | – |
| 2390–2483.5 MHz | Fixed and Mobile | Shared | 65 (dBm) | 20 (dBm) |
| 2500–2690 MHz[a,b] | Fixed and Mobile | Non-federal | 65 (dBm) | 20 (dBm) |
| 3550–3700 MHz[a,b,c] | Fixed and Mobile | Shared | 65 (dBm) | 20 (dBm) |
| 3700–3980 MHz[a,b] | Mobile | Non-federal | – | 20 (dBm) |
| 5850–5925 MHz | Fixed and Mobile | Shared | 65 (dBm) | 20 (dBm) |
| 5925–7125 MHz[b] | Fixed and Mobile | Non-federal | 65 (dBm) | 20 (dBm) |
| 27.5–28.35 GHz | Fixed and Mobile | Non-federal | 65 (dBm) | 20 (dBm) |
| 38.6–40.0 GHz | Fixed and Mobile | Non-federal | 65 (dBm) | 20 (dBm) |

[a] Commission rules do not permit airborne use on all or portions of these bands.

[b] Any experimental use must be coordinated with authorized users and registered receive-only fixed satellite earth stations.

[c] Operations must be coordinated with a spectrum access system administrator.

AERPAW is exploring with the FCC to expand its FCC-IZ with additional bands and to cover a larger geographical area.
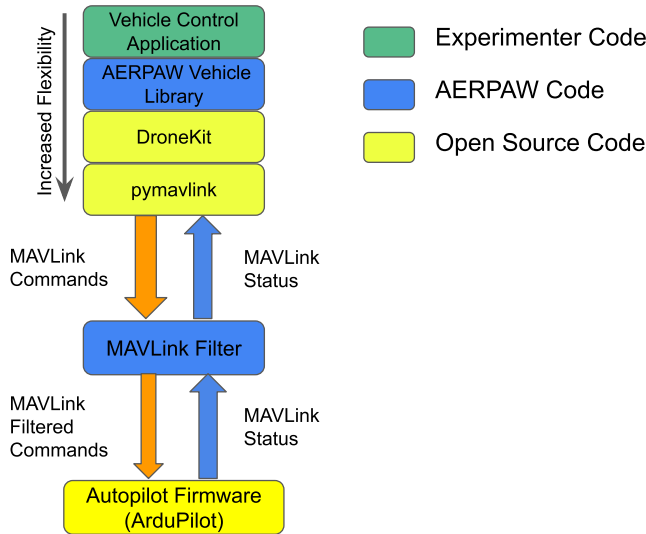


**Fig. 8.** AERPAW vehicle control stack.

More complicated swarm experiments with a larger number of drones and including communication links with SDRs can be easily carried out using the same workflow. Autonomous decisions can be integrated into the experiment, where the drones can make next waypoint decisions based on the observations of wireless signals.

Other testbeds can, of course, use alternate methodologies for providing programmatic online trajectory control to experimenters, and repeatability of mobility profiles for experiments. We have described AERPAW's approach above not to advocate it as the only way, but rather to articulate the level of programmability and repeatability that experimenters should be able to expect from a testbed facility.

### 4.4. Emulation support in development environment

AERPAW has well-articulated emulation support for both RF and aerial mobility aspects of experiments. In the "Development session" mentioned earlier, users can prepare their experiments with fully repeatable trajectories and wireless propagation. The main goal of providing the emulation environment is to allow users to develop their experiments in a safe and fully repeatable environment, which is also commonly referred to as a "digital twin".

Fig. 10(a) depicts an example experiment comprising a portable node on the left and a fixed node on the right while deployed in the emulation environment. In emulation mode, the experimenters' code (encapsulated in the two E-VM, and shown in green in the picture), is running with no modifications in comparison with an experiment in testbed mode. In contrast, in emulation mode, the vehicle and the wireless channel are emulated, thus allowing for a full software emulation, amenable to cloud deployment.

For vehicle emulation, we use an open-source available emulator that has been developed by the ArduPilot community, which features as its main characteristic the use of the *same* firmware as the autopilot we use on all our vehicles (at this time, drones, rovers, helikite, and a push-cart). Careful comparisons between the performance of the emulated vehicles and the testbed vehicles show that the vehicle emulator is performing very realistically.

In contrast, for the wireless channel emulator (CHEM), to the best of our knowledge, there is no open-source solution that satisfies all our requirements; therefore, we developed our own solution. Fig. 10(b) shows the main components involved in the CHEM. In general, each radio-enabled node in the testbed is capable of both transmitting and receiving radio signals, which we capture at baseband, IQ level. The IQ samples are sent to the channel emulator, which then "propagates" them to the corresponding receivers. The propagation in CHEM is controlled by the channel control module, which dynamically computes a channel matrix based on both dynamic information (e.g., the current
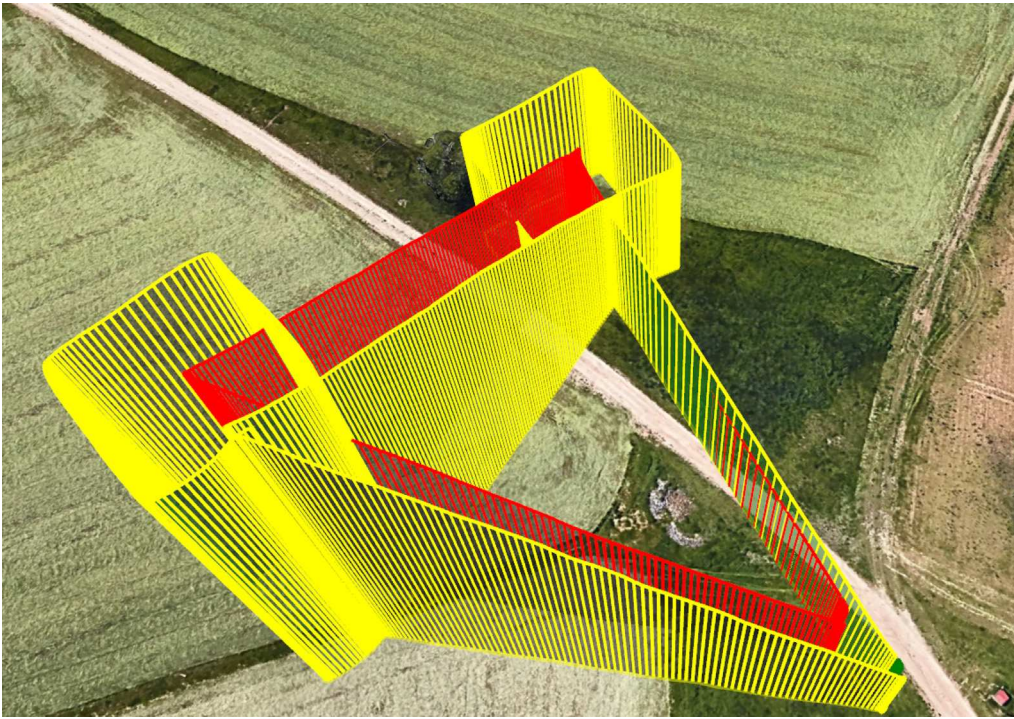
**Fig. 9.** Sample vehicle experiment with two coordinated drones: the tracer (red) goes through a list of waypoints, while the orbiter (yellow) orbits around the tracer while at the waypoint.

mobile node positions and orientations), as well as static information (e.g., position of the fixed nodes, antenna patterns, transmitter gains, etc.).

The CHEM supports several features, including free space and two-ray ground propagation models, two noise models, MIMO channels, up to 100 MHz of instantaneous bandwidth, multi-rate processing, different antenna patterns, multiple frequencies, and, importantly for efficiency, suppressing silences for bursty traffic. Note that there is a gap between the propagation environment in real world and that supported in CHEM. Since the flight area for AERPAW is a rural environment, the two dominant multipath components are that of line-of-sight and ground-reflected paths, which are also captured by CHEM. Still, there are many trees and a few buildings in the environment. Moreover, the roll/pitch/yaw of the drone may cause signal fluctuations due to changes in the antenna orientation. There may be fluctuations due to Doppler effects from the mobility of the drone, and micro-Doppler effects from the drone's propellers. There may also be additional RF front end effects and the USRP measurements need to be calibrated. At this time, AERPAW team provides representative real-world signal measurements from the field to the experimenters (see e.g. [74–77]), and they can calibrate their measurements based on the specific experiments that they work on in the development environment. AERPAW will be upgrading its digital twin to support wider range of propagation conditions that are representative of communications with drones and the conditions in the Lake Wheeler Flying Field in the future.

Once again, we have described AERPAW's approach above not to advocate it as the only way, but to articulate the level of emulation support we find required for an Open RAN testbed. Regarding AERPAW itself, while it has a good base from which to provide emulation support for Open RAN experiments, it would remain a non-trivial task to develop/procure and incorporate the large volume of software modules that would be required to be integrated into this framework in order to provide emulation support for a comprehensive complement of Open RAN experiments. In the next section, we return to this topic briefly.

### 4.5. Programmability, radios, software stack

AERPAW does not currently incorporate a full reference O-RAN implementation, although some parts exist. Table 7 indicates various AERPAW features and capabilities related to Open RAN. The edge–cloud model of companion computers at every AERPAW Radio Node (including both fixed and portable nodes) allows for an easy transition into Open RAN softwarized radio modules, as such modules become available and integrated into the testbed.

The Software Defined Radios of AERPAW represent a potential strength in a possible transition path to full Open RAN support since experimenting with evolving or innovative radio protocols is reduced to an exercise of software development and integration.

AERPAW team provides a variety of SDR sample experiments for experimenters to work with using open-source software and USRP SDRs from NI. Any AERPAW user can start with one of these experiments and develop their code further to research e.g. different protocols and waveforms. AERPAW presently supports four different sets of open-source software for SDR experiments: srsRAN [63, §4.1.1], OpenAirInterface [63, §4.1.2], GNURadio [63, §4.1.3], and Python scripts [63, §4.1.4]. A variety of sample experiments are provided in AERPAW's user manual for each case under Section 4.1 [63, §4.1].

These sample experiments also provide code for measuring the most pertinent KPIs we identified in Section 2.2 as foundational, namely "UE link quality – uplink and downlink", etc. on top of srsRAN, OAI etc. software; in other words, the existing AERPAW Sample Experiments already integrate the monitoring of these KPIs. As AERPAW integrates an Open RAN stack, it will be necessary to transition these to the new Open RAN Sample Experiments that will be created. The monitoring code uses standard, open tools such as iPerf that are agnostic to the underlying connectivity software, and results are saved in open format files such as CSV.

In Table 5, we provide a list of SDR sample experiments that are currently available or to be available by the end of AERPAW's Phase-2 (May 2023). An additional set of SDR experiments is expected to be added for general availability by the end of Phase-3 (expected
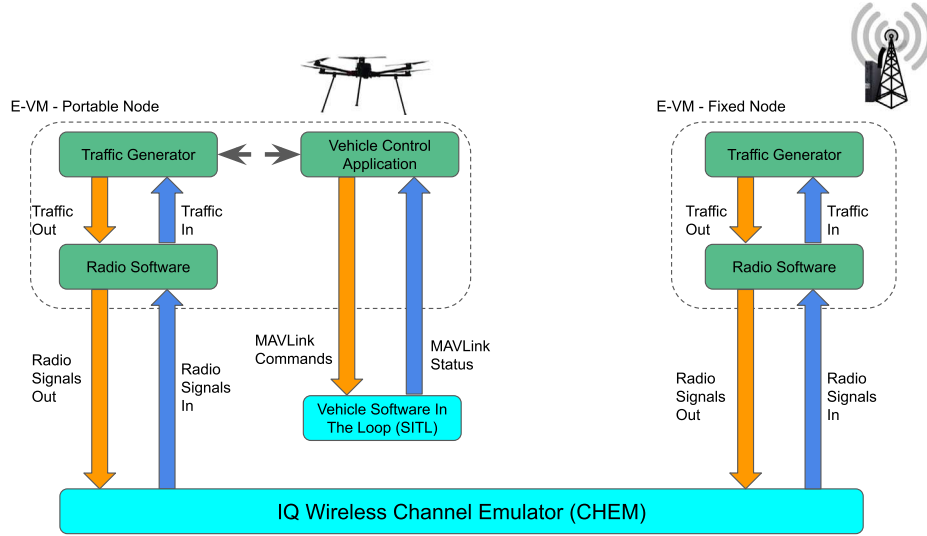
(a) AERPAW emulation environment overview for one mobile node and one fixed node.
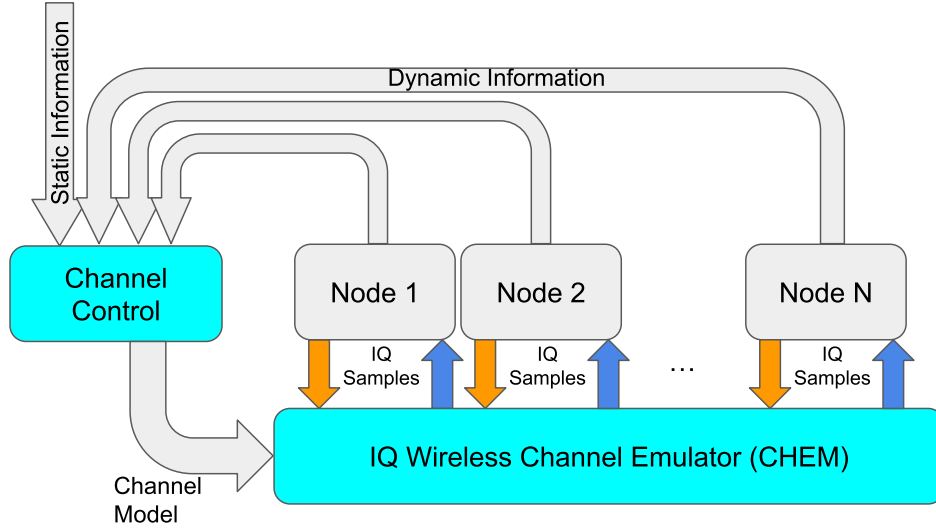


(b) AERPAW wireless channel emulator overview.

**Fig. 10.** AERPAW development environment (digital twin) overview.

May 2024). All these experiments are tested both in the development environment and the testbed environment of AERPAW. It should be clarified, that although AERPAW provides sample software for a large set of tasks, during the experiment development process any experimenter can install any software they desire in their containers (as long as the software is able to run in a docker container): the experimenters have root access to the containers and Internet access, so standard software installers (e.g., apt) can be used to install any package that the experimenter desires. The installed software is then transferred to testbed execution when the containers are transferred. While experimenters can also bring their own software to the platform, AERPAW cannot guarantee that they will work smoothly with the existing AERPAW hardware and software, and the development environment. For further details, readers are referred to AERPAW's user manual [63, §4.1].

AERPAW also includes similar prepared experiment profiles for commercial radio equipment available in the testbed (see Table 6), but they are relevant in the Open RAN context mainly as potential support equipment, so we do not discuss them further here.

### 4.6. O-RAN testing for controlled air mobility

AERPAW has applied to become a North American OTIC in the Research Triangle Area, to join other OTICs listed in Table 2. In addition to its experimentation capabilities reviewed earlier in this paper, AERPAW partnered with Keysight for O-RAN testing for controlled air mobility. As part of this effort, AERPAW acquired and is operating the Keysight Open RAN Architect (KORA) solutions package for O-RAN testing. Fig. 11, taken from [79], summarizes various different interfaces and approaches that an O-RAN system can be tested. Initially, the AERPAW team acquired UESim, CoreSim ORAN Studio (ORS), ORU Conformance, and RIC Testing KORA packages, and will focus on O-RU and RIC testing with support of controlled air mobility scenarios. AERPAW expects to expand testing scenarios in the future. Note that (in keeping with the distinction we drew in Section 2.2) this envisioned future OTIC role of AERPAW is distinct from the potential of AERPAW as an Open RAN *testbed* facility.

### 4.7. Summary - open RAN related components of AERPAW

While AERPAW has not been designed initially as an Open RAN testbed, its open, modular, and flexible design allows possible expanded

**Table 5**

AERPAW example experiments with SDRs. Experimenters can initiate their development in AERPAW's digital twin using these readily tested example experiments and expand them to study their own research ideas.

| Software | Sample Experiment | Comments |
|---|---|---|
| srsRAN | SE1: Multi-node LTE SISO | Complete E2E LTE network with multiple srsUE, and one srsENB and srsEPC |
| | SE2: LTE Cell Scan | Search for LTE cells and capture key parameters of interest |
| | SE3: Two-Node LTE MIMO | Complete E2E 2 × 2 MIMO LTE network, using srsUE with srsENB and srsEPC |
| | SE4: Multi-Node IoT | Basic NB-IoT signaling between the eNB and UE nodes |
| | SE5: LTE Handover | Complete E2E LTE network with S1 handover, using srsUE with srsENB and open5GS |
| | SE6: Single-Node 5G SA | Complete E2E 5G SA network, using srsUE with srsENB and open5GS |
| OAI | OE1: Two-Node LTE SISO | Complete E2E LTE network, using OAIENB and srsUE |
| | OE2: Single-Node 5G SA | complete E2E LTE network, using OAIGNB and srsUE |
| GNU Radio | GE1: OFDM TX-RX | Send and receive data using an OFDM waveform |
| | GE2: Channel Sounder | Pseudo-random sequence of bits are transmitted/received for channel sounding |
| | GE3: LoRa PHY TX0RX | LoRa transceiver with all the necessary receiver components |
| UHD Python-API | UHD1: Spectrum Monitoring | Sweep based spectrum monitoring between 87 MHz and 6 GHz |
| | UHD2: IQ Collection | IQ samples are collected at desired center frequencies with some sampling rate for a specified amount of duration |

**Table 6**

AERPAW example experiments with commercial RF hardware.

| Software | Sample Experiment | Comments |
|---|---|---|
| Ericsson | EE1: 5G Modem RF Logging and Throughput | Quectel modem logs various KPIs from 4G/5G Ericsson network |
| Keysight RF Sensors | KRSE1: Spectrum monitoring | Monitor and record spectrum up to 6 GHz |
| | KRSE2: Signal classification | Classify and detect a variety of signals based on RF signature |
| | KRSE3: Signal source tracking | TDOA based localization of a signal source by passive monitoring of its RF signature |
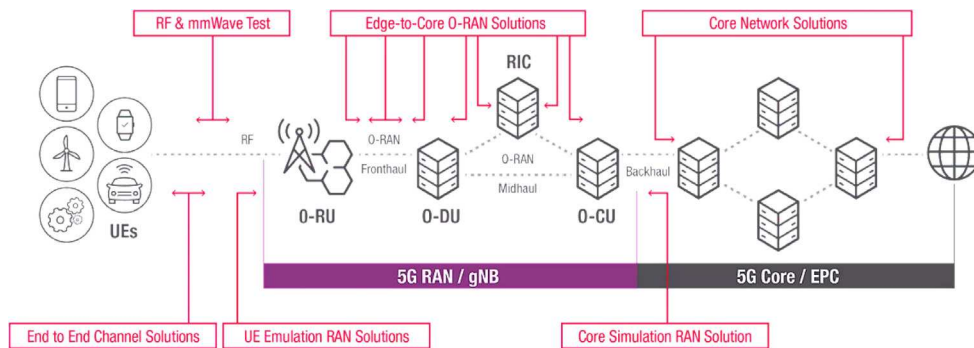


**Fig. 11.** KORA O-RAN testing solutions from Keysight [79] deployed at the NSF AERPAW platform.

support for Open RAN use cases as a living lab for UAVs with comparative ease. The AERPAW team contributed to a survey in November 2022 developed by the recently established Open RAN working group of the National Spectrum Consortium (NSC) [80]. This survey was shared by NSC members with existing testbed platforms that may potentially support Open RAN experiments in the future. In Table 7, we present a revised version of NSC's Open RAN survey and include comments on AERPAW's features and capabilities that can support Open RAN experiments with controlled aerial mobility. In particular,

we highlight open and programmable E2E network capabilities as well as commercial 5G equipment deployments in AERPAW, on-site access to wireless spectrum, different experimentation capabilities supported, compute nodes, unique use case testing scenarios, testing types, among other related platform features.

The information provided in Table 7 relates specifically to the match and extensibility of AERPAW as a meaningful Open RAN testbed for use cases with controlled air mobility. However, the exercise of preparing this table affords us practical insights into designing and building such

**Table 7**
AERPAW features and capabilities related to Open RAN.

| Capability | O-RAN Related Components | AERPAW Availability |
|---|---|---|
| Open and Programmable E2E Network | Multiple SDRs connected to power and network backhaul | USRPs, Keysight RF sensors |
| | Indoor wireless operations in a lab | N/A |
| | Outdoor wireless operations | Rural farm and urban campus |
| | Open 5G mobile cores | Open5GS |
| | Open fronthaul interface for testing open RUs | Not currently available |
| | Open source software stacks ready to use with or without additional software development | srsRAN, OAI, GNURadio, I/Q collection with sample experiments [63] |
| | Open source RIC implementation | Not currently available |
| | BYOD operation | Yes (on a case-by-case basis) |
| | BYOS operations | Yes (on a case-by-case basis) |
| | Bare metal for software installations | Not currently available |
| | Containers for software installations | Yes – both in emulation and testbed modes |
| | Remote access to network resources | Yes during development (emulation) mode, not normally during testbed mode |
| E2E Network with Commercial Equipment and Swappable Components | Commercial equipment | Ericsson 4G/5G network |
| | Indoor wireless operations | N/A |
| | Outdoor wireless operations | Rural farm area |
| | Commercial 5G mobile cores | Ericsson NSA core network (Release-15) |
| | Includes one or more of a commercial RIC, CU, DU, and RU | Not currently available |
| | Open fronthaul interface enabling testing of open RUs to support different physical layers | Not currently supported |
| On-site Access to Spectrum | Unlicensed or ISM band | 900 MHz for aerial communications with SDR front ends |
| | CBRS spectrum and CBRS SAS features | N/A |
| | Licensed spectrum from a spectrum owner | N/A |
| | Experimental or Innovation Zone licensed spectrum | Yes – FCC Innovation Zone with 13 bands in 0.6–40 GHz [63] |
| Techniques | Channel emulation systems | Software emulation available now [63], Keysight Propsim (32 ports) channel emulator in the process of integration |
| | Multiple modes of massive MIMO | Not presently available – mmWave UAV capabilities with 4 × 4 Sivers phased arrays in development |
| | Emulation capabilities for the RIC, CU, DU, RU, and UE | Presently not available |
| Compute Capacity | One optical hop | Yes |
| | Edge compute | Yes – Dell 5820 Server at fixed nodes, Intel NUC (i9) at portable nodes carried by AERPAW vehicles |
| | Public cloud computing | Not presently supported |
| Unique Use Case Testing | Drone support | Multiple different custom drones for different use cases |
| | Rural and urban environment | Yes (autonomous drone experiments available only in rural) |
| | Military base | N/A |
| | Smart agriculture | Deployment in Lake Wheeler agricultural farm of NC State [63] |
| Testing Types | Research and development | Free access by NSF-funded academic researchers, charge-based access for other researchers |
| | Compliance (3GPP, ETSI, O-RAN, etc.) | 3GPP compliant open-source and commercial 4G/5G hardware/software |
| | Interoperability | Partial |
| | Security | Partial |
| | Performance/stress testing | Partial |
| Others | Research staff availability | Yes (multiple research associates/students for research support) |
| | Operational staff availability | Yes (multiple research associates/students to support experiments) |
| | Wireless certification program | Not presently supported |
| | Established connections to standards/specifications organizations | NextG Alliance, Open Generation Alliance, GUTMA, Linux Foundation InterUSS Platform [78] |

an Open RAN testbed, to complement our observations in Section 2, and we pass these on to the community here.

Regarding the use cases described in Section 3, AERPAW currently supports UAVs serving as UEs, where the UAVs, connected to a ground BS, carry high-resolution cameras and/or sensors to collect real-time radio data and transmit it back to the ground BS. This data can be used to identify potential signal interference sources and report information about application performance. Additionally, AERPAW has the potential to implement the remaining scenarios due to its controlled mobility and the implementation of the existing radio facility.

**5. Representative results related to open RAN and controlled air mobility**

In this section, we present two early representative experiments from AERPAW that are of relevance for Open RAN experiments. We also elaborate on other possible experiments of relevance to Open RAN that may be supported in AERPAW in the future.

*5.1. RAN slicing xApp experiments*

In this section, we provide representative results using the RAN slicing xApp and srsRAN, using the framework by the NSF POWDER
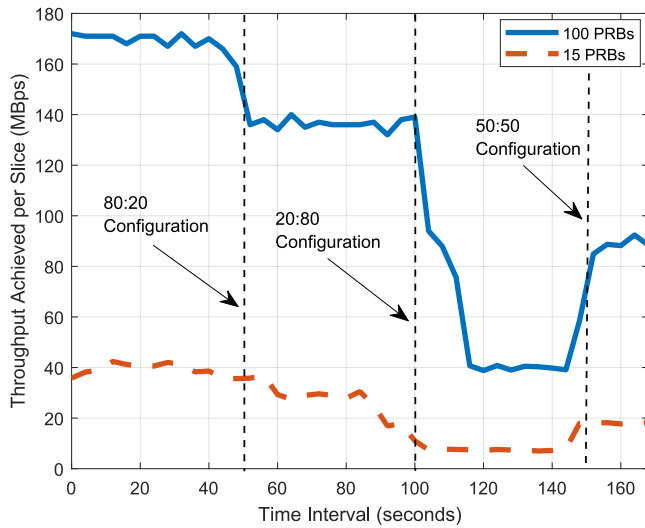
**Fig. 12.** Representative results on O-RAN slicing xApp using srsRAN with two UEs.

Wireless platform [81], executed at the AERPAW testbed. (Note that these features have not yet been integrated into the AERPAW's development and transition-to-testbed environments; we are exploring integration options at this time). The goal is to dynamically create network slices and observe the effects of slice reconfiguration with a TCP stream on the performance of a UE. A near Real-time RIC is deployed as part of two separate Kubernetes clusters. Detailed steps are provided in [82], we will provide a high-level overview of the architecture. The *RIC cluster* is used for deploying the platform and applications which are part of the RIC, whereas the *Aux cluster* is used to deploy other auxiliary functions. The RIC Kubernetes cluster installation is done through configuration scripts and pre-generated helm charts for each of the RIC components. Once the process is done, we created a persistent volume through a storage class for the influxDB on the RIC platform namespace. Once the RIC platform is deployed, a modified E2 termination is created which has few services enabled to communicate and exchange messages between RIC and E2 Agent [82].

Once the Kubernetes clusters are deployed, we can deploy the Near Real-time RIC using a RECIPE file which provides customized parameters for the configuration of a particular deployment group. This Recipe file can be tinkered with if we want to change any configuration to suit our requirements. Next is the installation of srsRAN components such as srsUE, srsEnB, and srsEPC which use ZeroMQ networking libraries. Since we use ZeroMQ mode, the 4G/5G network can be set up using a single machine that hosts both the RIC and srsRAN components. Finally, the xAPP is onboarded and deployed on top of the Near real-time RIC and full integration is completed.

Using this setup, we create two network slices in a work-conserving mode and bind two srsUEs to these network slices. Some representative results are presented in Fig. 12 for two different bandwidths, which show the throughput of one of the UEs. We configure the slice scheduler in steps to alter the proportionate scheduling in different ways and observe the effects on the TCP stream for the UE [83,84]. An Iperf server is created on the UE namespace to observe the effects of dynamic RAN slicing and a corresponding Iperf client [85]. We create two slices, referred to as *fast* and *slow*, where each slice can be dynamically configured to share the bandwidth. For the baseline scenario, the full bandwidth of 15 PRBs (100 PRBs) is initially allocated to the unsliced UE which gives a throughput of around 35–40 MBps (170 MBps) as illustrated in Fig. 12.

After this, the resources are distributed with the 80:20 configuration among the two UEs. The results in Fig. 12 show that the UE's throughput falls to 27 MBps (140 MBps) for this configuration, and when

the priorities are inverted between the fast and slow slices to 20:80, the throughput further reduces to 6–7 MBps (40 MBps). Finally, when the priorities are equalized to 50:50 configuration, the throughput increases to 16–17 MBps (70 MBps) for the first UE. The results can be easily extended to a larger number of UEs and more complicated resource configurations.

Our future work includes implementing this same scenario in AER-PAW's development and testbed environments with multiple controllable vehicles. The throughput needs and the link qualities of UEs will change dynamically over time as the vehicles move around, and there is a need to have a dynamic slicing mechanism that satisfies the requirements of individual network slices. AERPAW can support development and testing in such dynamic RAN slicing scenarios, first in the emulation environment, and then in the testbed mode with realistic propagation conditions. Programmable mobility with multiple vehicles in both environments and will make it possible to have a testing environment that provides repeatable measurements involving precise mobility control for the UEs, and in some cases, mobile relays and mobile base stations with wireless backhaul.

### 5.2. I/Q sample collection experiments

In Fig. 13, we provide representative results for the UHD2: IQ collection sample experiment shown in Table 5. The UAV is programmed to fly at five different altitudes and the USRP B205mini at the UAV collects IQ samples centered at 3.51 GHz with a sampling rate of 2 MHz. The only signal that can be observed in the spectrogram in the same band is an LTE signal of 1.4 MHz bandwidth, transmitted from a USRP B205 mini that runs srsRAN at our LW1 fixed node. We post-process the collected I/Q samples using Matlab's 4G toolbox, obtain RSRP for each I/Q sample location, and plot the RSRP over the trajectory. Additional details of the measurement setup and representative results are available in [77] using further post-processing with Matlab's 4G toolbox, such as coherence time and coherence bandwidth with respect to the distance between the UAV and the fixed node, kriging interpolation of the received signal across the whole 3D volume, channel estimation, synchronization procedures, among others.

A similar experiment can be carried out to capture I/Q samples and evaluate the KPIs for any Open RAN based 5G system with varying locations of UAVs and UGVs. One or more of the SDR, commercial wireless, or vehicle control sample experiments from AERPAW's sample vehicle experiment repository, such as the one illustrated in Fig. 9 above, can be used simultaneously with the I/Q sample collection experiment, to collect the raw I/Q data at the finest granularity and post-process them in Matlab's 4G and 5G toolboxes to generate desired KPIs. Such data collected in realistic propagation conditions can be made publicly available to the research community for furthering the research in controlled aerial mobility technologies.

### 6. Conclusion

Open RAN expands the capabilities of 5G to support features and functions tied directly to use cases. Disaggregation and virtualization are well suited to UAVs/drones which will continue to grow and become a much greater part of the 5G network from a UE or acting as an O-RU, O-DU, or O-CU component of the network architecture. However, testing and validation are critical to successful integration into 5G and the expansion of Open RAN network capabilities.

Creating a testbed that supports UAVs poses challenges to meeting all the demands from the physical network to Open RAN interoperability needs. For the UAV market to grow and flourish testing and validation are necessary. As rules and regulations remain volatile in the immediate future, a UAV Open RAN lab can provide extremely valuable technical results to inform such actions.

In this paper, we have provided conclusions drawn from our experience and expertise gained from designing AERPAW, a one-of-a-kind
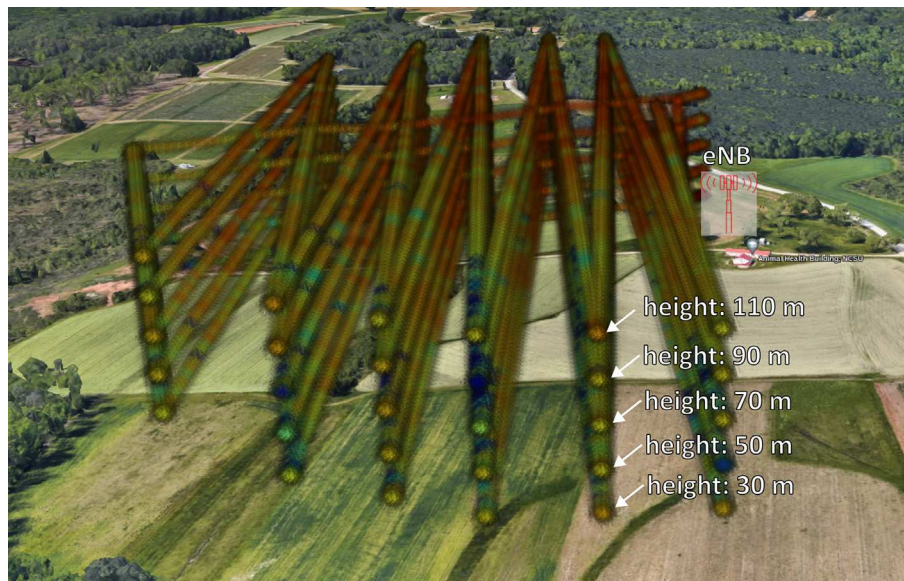
**Fig. 13.** I/Q sample experiments representative results: LTE reference signal received power (RSRP) at five different UAV altitudes.

public advanced wireless testbed that provides programmable radio and vehicle control in a realistic outdoor area of considerable span and also reflected on its fit as a possible Open RAN/UAV testbed in future. We hope these observations may be helpful to the community of designers of other such facilities

**CRediT authorship contribution statement**

**Magreth Mushi:** Writing – original draft. **Yuchen Liu:** Writing – original draft. **Shreyas Sreenivasa:** Writing – original draft. **Ozgur Ozdemir:** Writing – original draft. **Ismail Guvenc:** Writing – original draft. **Mihail Sichitiu:** Writing – original draft. **Rudra Dutta:** Writing – original draft. **Russ Gyurek:** Writing – original draft.

**Declaration of competing interest**

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**Data availability**

Data will be made available on request.

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