Abstract—Cellular network-connected unmanned aerial vehicles (UAVs) experience different radio propagation conditions than radio nodes on the ground. Therefore, it has become critical to investigate the performance of aerial radios, both theoretically and through field trials. In this paper, we consider low-altitude aerial nodes that are served by an experimental cellular network. We provide a detailed description of the hardware and software components needed for establishing a broadband wireless testbed for UAV communications research using software radios. Results show that a testbed for innovation in UAV communications and networking is feasible with commercial off-the-shelf hardware, open-source software, and low-power signaling.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are increasingly popular in the commercial sector and are considered one of the industrial verticals of the fifth generation of mobile communications (5G). UAVs can support intelligent transportation systems through traffic monitoring, accident reporting, and aerial delivery of cargo and medication, among others. Among many applications, UAVs can monitor crops, detect weeds, gather sensor data, and assist with search and rescue and disaster recovery operations [1]. Fig. 1 illustrates this.

The characteristics that make a UAV particularly suitable for the above-mentioned applications are the strong line of sight (LOS) links, 3D mobility, low cost, and ability to operate in a hostile environment. The cellular network performance can be improved with UAVs by implementing stronger security mechanisms [2], extending the coverage, and improving the capacity [3]. This is being standardized by The Third Generation Partnership Project (3GPP) [4].

The 3GPP Technical Report (TR) 36.777 and Technical Specification (TS) 22.125 define the essential requirements for providing unmanned aircraft system (UAS) services through long-term evolution (LTE) networks. TR 23.754 and TR 23.755 identify the network infrastructure and the application architecture to support UAV-enabled applications and use cases in 5G networks. TR 33.854 and TR 23.755 identify the network infrastructure and the application architecture to support UAV-enabled applications and use cases in 5G networks. TR 33.854 specifies the requirements and procedures to provide secure communications services to UASs served by 3GPP networks. The International Telecommunication Union (ITU) and the IEEE provide complementary standards for UAV applications and use cases [5], [6].

UAVs are not only considered as user equipment (UEs) in the cellular network, but also as network support nodes. They have the potential to facilitate reliable, secure, and efficient wireless access [7]. A large number of applications involving UAVs and advanced wireless communications are expected to be developed in the coming years. To realize this vision, it is necessary to have flexible research platforms and testbeds that are widely accessible. This will accelerate research and development (R&D) that will provide practical insights on the specific services that cellular networks should offer to enable safe and efficient operation and cooperation among UASs. The 3GPP provides initial performance requirements for the network to support command and control and video transmission from UAVs [4]. Cellular network technology and procedures need to evolve to, among others, improve the 3D coverage and effectively handle the challenging interference scenario between UAV and terrestrial UEs.

Software defined radios (SDRs) can be used with a UAV for rapid radio prototyping and experimentation. An SDR does the radio frequency (RF) data acquisition/generation and data conversion for waveforms and protocols to be processed in software [8]. Using a pair of Universal Software Radio Peripherals (USRPs) and open-source LTE software srsRAN, [9] reports average throughput and signal-to-noise ratio values at 10, 25, and 50 m UAV altitudes from the ground SDR base station (BS) as 5.5, 2.0, 4.5 Mbps and 10.0, 7.5, 9.0 dB, respectively, for a 10 MHz frequency-division duplex (FDD) LTE system at 3.7 GHz. Those values are rather low, even without an external power amplifier (PA). This may stem from choosing too high USRPs gains resulting in signal distortion and self-interference from the design lacking isolation between the transmit and receive antennas [9]. Another trial evaluates the performance of the UAV as a relay between the ground BS and UE [10]. The open-source OpenAirInterface (OAI) software with a USRP on board the UAV provides the experimental LTE aerial relay (AR). The measurements show that the throughput slightly improves when the signals are relayed through the AR, specifically for non-LOS links between the BS and the UE. In another research project [11], the UAV with a USRP and srsRAN is deployed as an aerial BS (ABS) that positions itself to maximize network throughput for three ground UEs. Throughput measurements were conducted in an outdoor drone cage over short distances.

The published SDR platforms’ evaluation results often do not provide the necessary performance because of poor design or operating decisions. The difficulty is to select, integrate, and configure the hardware and the software for providing a flexible and accessible platform that can provide near commercial-grade performance and that can be scaled for enabling cellular-connected UAV research in a production-like environment.

The purpose of this paper is to identify the requirements, the design tradeoffs, the components and practical design and configuration choices for building a reproducible open-source SDR platform that provides the necessary interfaces and performance figures for enabling unlimited research opportunities
Fig. 1: Emerging applications and use cases for networked UAVs.

with cellular network-connected UAVs. The proposed platform is the basis for the first SDR experiments offered through the *Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW)* [12].

The rest of the paper is organized as follows: Section II introduces the platform requirements. Section III assesses the design options, tradeoffs, and component choices. We show early results and offer guidelines for research in this area. Section IV discusses the key challenges and directions for advanced wireless R&D with UAVs. Section V provides the concluding remarks.

**II. REQUIREMENTS OF CELLULAR NETWORK-CONNECTED UAV RESEARCH PLATFORMS**

The high demand for UAV integration into cellular networks requires a research platform that can evolve with technology. Deploying a production-like 4G/5G experimental cellular network requires implementing the radio access network (RAN), the backhaul, and the core network (CN). This is the goal of AERPAW, a public-private partnership project that is developing and operating a large-scale testbed for advanced wireless research with UAVs. The requirements for the open-source SDR research platform are

- 3GPP standard-compliant cellular communications system that performs according to industry benchmarks,
- Flexible and modular radio interface, supporting various cellular network-connected UAV experiments,
- Effective integration of the radio system with the UAV, subject to the UAV’s space, weight and power constraints,
- Open-source software that is maintained and that implements the RAN, the backhaul, the CN, and the UEs,
- Commercial off-the-shelf (COTS) hardware that is widely available and that is popular among researchers,
- Inter-operable and well-supported software and hardware,
- Reproducible platform and experiments,
- Open application programming interfaces (APIs),
- Full control over the experiment (radio and vehicle), and
- Scalable and portable platform that facilitates integration with other testbeds, vehicles, or infrastructure.

The above requirements translate into specific requirements for the different building blocks of the platform. These are summarized in Table I and elaborated in continuation.

**Data Conversion:** The wireless transmission and reception of software-defined waveforms requires data sampling and up/down conversion. These processes are facilitated by commercial SDR hardware, which should support commercial 4G and 5G sampling rates, instantaneous bandwidths of at least 20 MHz, and frequency agility. Moreover, it should allow multi-channel communications to support transmit (Tx) and receive (Rx) diversity, multiple-input multiple-output (MIMO) communications, and beamforming.

**RF Front End:** The goal is to have a modular and flexible RF front end for supporting multiple bands, providing enough RF transmission power and filtering to comply with spectrum regulations, Tx-Rx antenna isolation to avoid receiver saturation, and enough gain to recover weak signals at the limit of the coverage area, initially defined as 1 km from the BS. The choice of RF components will eventually be driven by the experimenter needs and the commercial availability of RF components for the desired frequency. Obtaining a local license to radiate from the ground and air is also necessary.

**Processing Unit:** The baseband processing has the highest computing demand of a cellular communications system. It can be executed on a general-purpose processor with sufficient processing power. The processor also needs to provide several network interfaces for data and control.
Power: Computers, SDRs, and active RF components need a power supply. The power requirements are defined by the RF and processing units, experiment configuration, and experiment duration.

SDR Software: AERPAW proposes to leverage popular open-source software libraries that implement modern RANs, CNs, and UEs. The reason is that the testbed is built for enabling global and cutting-edge research, which can be excelled when the code is open, maintained, and easy to modify. This enables rapid prototyping and experimenting variations to the RF signaling and protocol processing. The main criteria for choosing a software library are its user community, COTS hardware compatibility and portability, and interoperability with other experimental or production radio equipment.

Experimental and Control Networks: The experimental network connects UEs to the RAN via SDRs and the RAN to the CN via radio, fiber, or copper. All BSs need IP connectivity to the CN to implement the S1 interface for authentication, mobility management, and so forth. AERPAW users submit their experiments and, when approved, the experiment runs in batch mode. However, for initial platform development and during regular operation, experiments are controlled by the testbed operator, who needs to be able to configure, start, stop, or pause an experiment as needed, e.g. when undesired situations are detected. Being able to connect to each SDR computer via secure shell (ssh) is the goal for initial development, testing, and experiment control.

UAS: The UAS is the UAV and its remote controller (RC). Unless a UAV flight waiver is obtained, a certified pilot must be in visual LOS with the UAV. The UAV needs to be robust enough to lift the experimental radio system payload. An experiment may encompass evaluating or choosing a UAV trajectory as a function of the observed radio parameters. Timestamped and location-specific data, typically provided by the onboard global positioning system receiver, therefore need to be logged and provided to the experimenter after the experiment.

III. SOFTWARE AND HARDWARE OPTIONS AND THE SYSTEM DESIGN TRADEOFFS TO MAKE IT ALL WORK

The selection of components depends on their compatibility, ease of integration, flexibility, scalability, performance, and availability. While we organize this section similar to the previous, the software (SW) and hardware (HW) interactions are critical for the choice of components to prototype an efficient platform that meets the outlined requirements. Table I lists the specific components of the proposed platform.

Fig. 2 shows the minimum necessary system components and the logical interfaces. Defining the components and interfaces facilitate scalability and portability.

A. Radio Network Hardware

Data Conversion: Among the examined options, USRPs offer several advantages: a wide set of board and RF module options, 56+ MHz instantaneous bandwidth per channel, and a single open-source hardware driver. There are lightweight and small form factor devices that fit well on a UAV. We chose USRPs mainly because of their flexibility and openness, their popularity among the broader R&D community, and their compatibility with advanced SDR software, the popular GNU Radio framework, and Matlab. USRPs have their limitations, including low Tx power, especially for wideband multicarrier waveforms, limited analog filtering, and interoperability issues among certain driver versions, devices, software, and frequencies. These can be overcome by careful hardware and software design, configuration, and systematic laboratory and outdoor testing. We use auxiliary SDR hardware, RF instruments, and open-source tools, such as iPerf, ping, Wireshark, and SDR-specific tools for signal and network analysis.

RF Front End: The output power of the USRPs alone is insufficient for establishing reliable communications links over more than a few 10s of meters; hence, a PA in the transmit chain is necessary. Given our goal to communicate over 1 km, our calculations have shown that a high linearity PA with a gain of 30-45 dB is needed. The 15 W PA from Table I requires a heavy heatsink and dedicated power supply and is recommended for the fixed node. The UAV imposes constraints on size, weight, and power. The smaller and lighter 1 W PA can be mounted directly to the payload chassis for cooling. Based on the maximum output power of the USRP
TABLE I: Requirements and proposed design for the SDR platform enabling 4G/5G cellular networked UAV research.

| System Features | Requirements | Components |
|-----------------|--------------|------------|
| **SDR** | Data conversion | - COTS SDR hardware with drivers that support sampling rates of modern wireless systems, permit a wide range of RF, and have broad research community support. | - B205mini-i USRP: Up to 61.44 MHz sampling rate, 56 MHz instantaneous bandwidth, 0 dBm maximum Rx power, low Tx output power \[^3]\), <8 dB noise figure (NF), 70 MHz to 6 GHz. |
| **Baseband/protocol processing** | - Multi-core x86 computer with 3 GHz or higher clock per core (at least 4 physical cores) with USB 3.0 or 10 Gbps NIC. | - Dell OptiPlex 7070 Micro (fixed node): Intel i9-9900 8-core processor, 32 GB RAM, USB3, two-port 10 Gbps NIC (SFP+), 1 Gbps NIC. - Intel NUC10 (NUC10i7FNK) (mobile node): Intel i7-10710U 4-core processor, 32 GB RAM, USB3, Thunderbolt 3, 1 Gbps NIC. |
| **Software** | - Supported open-source software libraries; closed source software can be useful, e.g. for baseline experiments. | - The latest USRP Hardware Driver (UHD) 4.0, srsRAN version 2010.1, open5GS version 2.2.9, and OAI version 1.2.2, are installed on Ubuntu 18.04 in Docker containers. |
| **RF Front End** | Amplifier | - Transmit PA for desired 1 km range; gain and other characteristics depend on the SDR and the output power it can cleanly produce for a wideband signal. - Low power consumption, weight, size, and cooling for mobile node PA. - Receiver LNA to improve reception range. | - Mini-Circuits (MC) ZHL-15W-422-S+PA: 15 W, 46 dB gain, 38-40 dBm output power at 1 dB compression, 49 dBm OIP3, 10 dB NF, 0.6-4.2 GHz. - MC ZVE-8G+ (mobile Tx) PA: 1 W, 34-36 dB gain, 32 dBm output power at 1 dB compression, 40 dBm OIP3, 4.5 dB NF, 2-8 GHz. - MC ZX60-83LN12+ LNA (Rx): 22 dB gain, 13-20 dBm output power at 1 dB compression, 30-35 dBm OIP3, 1.4-2.3 NF, 0.5-8 GHz. |
| **Filters** | - Eliminate harmonics and spurs in the transmitter. - Limit the amount of undesired signals entering the receiver, yet provide frequency agility. | - MC VLF-4400+ (Tx): low pass filter DC-4400 MHz passband (PB), 3 dB loss at 5290 MHz. - MC VBFZ-3590+ (Rx): bandpass filter with 3000-4300 MHz PB. |
| **Antennas** | - Broad coverage and frequency agility. - Small and lightweight for the UAV node. | - Mobile Mark RM-WB1-DN-B1K (fixed node): 617-960 and 1700-6000 MHz, 3 dBi peak gain, up to 10 W. - Octane Wireless SA-1400-5900 (mobile node): 1400-5900 MHz, up to 500 mW. |
| **Network** | Experiment network | - Reliable interface between the RAN and the CN. | - Ethernet or WiFi6 (AX4800 router) for the backhaul and BS-BS links (X2 interface). |
| | Experiment control | - Reliable wireless side channel for aerial SDR experiment control. | - Private IP network using ssh via WiFi6. |
| **UAS** | UAV | - Easy takeoff and landing, hovering capability, and 5 kg payload capacity. | - DJI Matrice 600: Hexacopter with 5.5 kg maximum payload and 6 x 5,700 mAh battery capacity (TB48S battery pack). |
| | UAV control | - Certified UAV pilot with RC and visual line of sight to the UAV due to current regulations. | - DJI Matrice 600 manufacturer supplied RC. On-site operator, one per UAV. |
| **Power** | Ground node | - Direct AC, if available, or a generator for powering computers, SDRs and RF components. | 2000 W portable gasoline generator with grounding rod collocated with each fixed node at the test location. |
| | Aerial node | - Autonomous (battery-powered) operation. | - Separate power sources for UAV and SDR payload. - The UAV comes with high-capacity batteries (30 minute flight). - 5S 3000 mAh LiPo battery for NUC10 + SDR, PA, and LNA. |

and any signal distortion, appropriate input power backoff to provide a clean transmission.

Our experimental license prohibits out-of-band transmissions. A well-specified low-pass filter in the transmit chain provides simplicity and frequency agility while mitigating potential RF harmonics. A wide bandpass filter (preselector) in the receive chain helps with minimizing interference while allowing frequency agility. The specific filters for the band of interest are provided in Table I and were selected because of their specifications and availability.

In the receive chain, a low noise amplifier (LNA) was anticipated, and experimentally verified, to improve the communications range. The power supply voltage for the LNA and 1 W PA are identical, thus saving weight on the UAV.

The USRP has internal variable gain amplifiers in the transmit and receive paths. They allow for a range of linear amplification \[^3]\), but these gains need to be carefully adjusted to optimize the connection depending on the PA and LNA specifications, the Tx-Rx antenna isolation, and the desired range. In general, the USRP Tx gain is set to the highest value to provide maximum signal strength while accounting for sufficient backoff to not damage the PA and avoid signal distortion, as shown in Fig. 3. The USRP Rx gain is set to be able to receive weak signals while avoiding receiver saturation from the desired signal, its own Tx signal, and any other signals falling into the passband of the preselector.

Because a duplexer would limit frequency agility, we choose to minimize self-interference by physically isolating the antennas both on the UAV and at the BS (Fig. 4). In order to ensure good aerial coverage and simplify deployment, we chose wideband omnidirectional antennas.

**Processing Unit:** Selecting the processing unit and SDR
should be done jointly and as a function of the SDR software. Because of the need for a small form factor, lightweight, and low power consuming processing unit for the UAV, we had to compromise the 10 Gbit network interface card (NIC). This left us with USB-driven USRPs and the powerful and compact Intel NUC10 computer (Table I), which has many USB 3.0 ports for driving multiple such USRPs. The NUC10 also has a modern WiFi chip, leveraged for experiment control. For the SDR BS, a multicore processor with highest per-core clock rates, a WiFi chip, and a 10 Gbit NIC are essential to support the necessary network interfaces of Fig. A high-end Intel i7 or i9 processor offers a high clock rate per core, can be packaged in a small form factor, and has a lower power consumption compared to high-end processors used for servers or workstations, easing field deployment.

**Power:** The choice of the power supply source for the mobile radio node will impact the UAV flight duration. Although it is possible to power the payload from the UAV power system, an additional battery will limit flight time loss in spite of the increased weight [14]. This payload battery is sized by calculating the maximum power requirements of the system from the component data sheets and multiplying by the desired flight time of 0.5 h. Recognizing that the maximum power case is a worst-case scenario, no additional safety margin is incorporated. This calculation yields a 3000 mAh battery as optimum. Payload and UAV batteries are swapped and recharged at the same time. A 2000 W gasoline generator using 0.5 gallon of fuel can supply the ground node equipment plus displays shown in Fig. for about 7 h.

### B. Radio Network Software

Both OAI and srsRAN have a fully functional 4G LTE protocol stack and are developing 5G systems in software. They support multiple SDRs and are popular among researchers and developers. OAI is built using scripts for creating the appropriate executables, whereas srsRAN uses a standard process for building from source. Both libraries run on Ubuntu, are well maintained, and new versions are regularly released.

Each software has advantages and disadvantages that make them useful for different experiments. Different modules of each software may be used to take advantage of their features. But this poses compatibility and interoperability challenges that may include incompatible interfaces or parameters. We analyzed the options and found that srsEPC is compatible with either the OAI BS (eNB) or srsENB and either combination supports the srsUE. Open5GS is compatible with srsENB and srsUE and supports handover.

When using different eNBs, the key parameters are those relating to the EPC connection, such as the mobility management entity IP address, tracking area, mobile country and network codes. Those parameters must match the EPC in order for proper communication to occur between them. Using an EPC from a different project, e.g. Open5GS with srsENB, requires that the UE information is entered into its database. RAN settings include LTE band or frequency and USRP gain.

### C. Network Interfaces

#### Experimental Network:

The experimental cellular network uses the wireless interface and networked computers for implementing the RAN and CN. The CN can be integrated with one BS but other BSs need to connect to it through a wired or wireless link. When deploying multiple BSs, the backhaul is ideally implemented via fiber. For flexibility, simplicity, and to not have to rely on costly infrastructure, we recommend setting up a dedicated WiFi network with directional antennas for higher range. A potential future solution is the integrated access and backhaul, which is an emerging 3GPP technology that future ground and ABSs will likely leverage [15].

#### Experiment Control:

For the experiment control interface, a cellular control link is a viable option for most places, but requires a data plan and lightweight yet quality LTE USB dongles. This is AERPAW’s choice. Below we present an alternative that works well with minimum dependencies and no additional payload.

WiFi6, or IEEE 802.11ax, is widely available. It can be configured to operate in the 2.4 or 5 GHz unlicensed band and implements multi-user (MU)-MIMO for improving range and capacity. The BSs and UEs need to be within the range of the WiFi access point (AP) for continuous experiment control. COTS directional antennas are widely available for these bands and one can be collocated with each ground node for interconnecting BSs and implementing the required interfaces. The NUC10 has an integrated WiFi6 chip and antennas, and it is therefore mounted upside down on the outside of the UAV payload cage (Fig. 4).

### D. UAS

The weight of the payload and desired length of flight are the dominant factors determining UAV selection. Our platform (including payload battery) weighs 2.2 kg and we desire
remains very high for more than 400 m horizontal distance. The throughput of the LTE frame is for control signaling which makes the theoretical UL and DL of 50 and 60 Mbps, respectively. About 25% of the eNB and achieves nearly the highest theoretical rates for the successful attachment of the aerial UE (AUE) with the eNB and where 5G systems will operate. The fixed BS is at the origin and the UA V at (distance, height) with respect to it.

approximately 30 minutes of airborne experiment time. These requirements drive the need for a medium lift vehicle like the DJI Matrice 600. For flexibility and exploratory research, we recommend manual control of the UAV flight during the experiment as opposed to waypoint-based flight path navigation. The control link is established through the standard RC provided by the UAV manufacturer and is independent of the previously discussed interfaces. Fig. 4 shows our aerial node.

E. Experimental Results

Here we present initial 3D coverage measurements in a rural environment. We operate an LTE experiment in FDD mode (FD-LTE) in 3GPP Band 22 (C-Band), where we have a license and where 5G systems will operate. The fixed BS is 2.5 m above ground. The UAV flight is over an agricultural field with LOS to the BS (Fig. 4). We implement the eNB and UE with srsRAN and the EPC with open5GS. The USRP Tx and Rx gains are 72 and 47 for the eNB and 75 and 35 for the UE. Fig. 3 shows the spectrum of the eNB Tx signal, the LTE downlink (DL), at full DL resource allocation at the output of 15 W PA for the above gains settings. After correcting for the splitter and attenuator losses in the spectrum analyzer path we obtain the average output power of 21 dBm at the eNB antenna port. Equivalent measurements at the mobile node yield about 15 dBm average UE Tx power for the proposed configuration. The differences in Tx gains are due to the higher PA distortion at the eNB, whereas the differences in the Rx gains are due to the lower Tx-Rx antenna isolation at the UE.

Fig. 5 presents our uplink (UL) and DL throughput measurements. A UAV position close to the eNB at low altitude prove the successful attachment of the aerial UE (AUE) with the eNB and achieves nearly the highest theoretical rates for the UL and DL of 50 and 60 Mbps, respectively. About 25% of the LTE frame is for control signaling which makes the theoretical maximum 50 and 75 Mbps, respectively. The throughput remains very high for more than 400 m horizontal distance from the BS at different UAV heights. The performance starts to degrade when the distance increases further as a result of the increased path loss, but is still well above 10 Mbps even beyond 1 km.

These results satisfy our goals to provide flexibility, performance, and enable scalable experiments. Compared to existing open-source SDR platforms and reported results, our platform offers high performance, range, and allows agility in frequency and flight trajectory. The platform can operate between 3.0 and 4.3 GHz, which can be further extended by changing the filters. All the deployed software is available for free download and use and is well maintained. All the hardware is widely available. The radio software and hardware choices are compliant with AERPAW and will be available through it for global researchers to use. One has still many choices, e.g. which UAV and frequency to use or how to implement the backhaul. This allows portability of our SDR platform with many customization and extension options for R&D.

F. Guidelines

A few important guidelines for interested researchers are provided below.

- COTS SDR Tx power levels are low and there is often little isolation between the Tx and Rx signal paths. This requires signal, gain, and interference analysis, especially when using PAs.
- The RF environment on the ground and in the air needs to be understood from the perspectives of the interference to and from the planned experiment. Adjacent channel signals passing the preselector of the SDR can cause aliasing or receiver saturation. Filters should therefore be used.
- Processors, interfaces, the software environment, the SDR software processes, and the SDR and RF hardware need to be examined in concert and tested exhaustively to identify and eliminate bottlenecks. Baseline performance metrics and benchmarks need to be defined and RF and system testing processes established to verify and calibrate the system configuration before each experiment.

IV. Challenges and Research Directions

The proposed platform has been developed to enable advanced research and help solving the challenges identified by industry and academia, including those described below.

Interference: The deployment of an aerial radio platform comes with various types of interference problems that can affect the network performance. In addition, the RF footprint of AUEs which typically have LOS channels with multiple ground BSs can severely degrade the capacity of the cellular network. Managing inter-cell interference (ICI) will be critical to enable coexistence between aerial and ground users. The air-to-ground (A2G) ICI will exist between a UAV in one cell and cochannel interference between terrestrial and AUEs associated with nearby cells. The conventional ICI that has been studied for terrestrial communications will not be valid for solving the A2G ICI problem. Therefore, interference management is a critical research direction for UAV integration.
into cellular networks.

**Cell Association and Handover:** Because antennas have specific RF patterns and there is typically no signal blockage in the sky as there is on the ground that is leveraged to deploy cell towers and define cells boundaries for terrestrial users, the traditional cell association and handover procedures will need to be revised to avoid frequent handovers and complex resource management. Aerial and terrestrial users may need to be treated differently. Advanced wireless technology, specifically beam-based access, can be leveraged for this.

**Limited Airtame:** Battery-powered multi-rotor UAVs have an airtime of about thirty minutes. Different solutions can be conceived to address this limitation: (1) Design and deploy tethered UAVs where high endurance is needed and low mobility is possible. Research needs to make drone tethers more available, flexible, and safer to use [14]. (2) Coordinate mobility is possible. Research needs to make drone tethers tethered UAVs where high endurance is needed and low mobility is possible. Advanced wireless technology, specifically beam-based access, can be leveraged for this.

**UxNB:** UxNB is The 3GPP’s term for UA Vs taking on technologies, as well as more energy-efficient UA V operation. and develop a combination of energy storage and charging more available, flexible, and safer to use [14]. (2) Coordinate mobility is possible. Research needs to make drone tethers tethered UAVs where high endurance is needed and low mobility is possible. Advanced wireless technology, specifically beam-based access, can be leveraged for this.

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