# Open-Source Software Radio Performance for Cellular Communications Research with UAV Users

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***Abstract*—An unmanned aerial vehicle (UAV) is both an enabler and user of future wireless networks. It experiences different radio propagation conditions than a radio node on the ground. Therefore, it is important to experimentally investigate the performance of cellular communications and networking innovations while serving aerial radios. In this paper, we examine the performance of low-altitude aerial nodes that are served by an open-source software-defined radio (SDR) network. We provide a detailed description of the open-source hardware and software components needed for establishing an SDR-based broadband wireless link, and present radio performance measurements. Our results with a standard compliant software-defined 4G system show that an advanced wireless testbed for innovation in UAV communications and networking is feasible with commercial off-the shelf hardware, open-source software, and low-power signaling.**

***Index Terms*—4G, 5G, AERPAW, cellular network, testbed, UAS, UAV.**

## I. Introduction

Unmanned aerial vehicles (UAVs) are considered by the commercial sector for a number of applications including intelligent transportation systems, aerial delivery [1], search, coordination, and rescue operations [2], and precision agriculture [3]. Another use for a UAV is that of an aerial base station (BS) serving a wireless network. The fifth generation of mobile communications (5G) framework considers UAVs as enablers for several industrial verticals.

An unmanned aerial system (UAS) consists of a ground station controller, usually a human operator, and the UAV. The unique characteristics of a UAV that make it particularly suitable for the above mentioned applications are its 3D mobility pattern, ease of maintenance, low cost, and ability to operate in a hostile environment [4]. The communications link between the terrestrial BS and the UAV must be secure, reliable, broadband, and of low latency. Steps to identify the challenges and solutions of emerging cellular networks to serve UAVs are being undertaken by the 3rd Generation Partnership Project (3GPP) [5]. Researchers have focused on analyzing cellular-connected UAV performance and how to optimize terrestrial network performance for serving aerial user equipment (UE). Exemplary theoretical works explore aerial coverage [6], aerial and ground interference [7], security [8], path planning design [9], and spectrum sharing [10].

While theoretical and simulation-based research is ongoing, it is critical to perform field testing to evaluate the performance of cellular-connected UAVs and assess the coverage and link reliability for meeting different quality of services requirements. The field tests can be performed using already existing commercial cellular networks or through ad hoc software-defined cellular networks. In terms of reliability, scalability, and security, it has been shown that using softwarization and virtualization with commercial-off-the-shelf (COTS) software-defined radio (SDR) solutions is more flexible than using commercially deployed cellular networks [11]. Results from testing the UAV communications performance when connected to commercial long-term evolution (LTE) networks have been reported in [12], among others. Others have illustrated the connectivity opportunities, gaps, and interference problems [13]. The 3GPP Technical Report (TR) 36.777 [14] discusses air-to-ground interference for UAVs connected to terrestrial LTE networks. Zeng et al. [15] and Yang et al. [16] discuss drone-enabled applications in the context of emerging 5G networks and indicate some of the early standardization efforts. On the other hand, there are very few measurement campaigns and testbeds that use SDRs for advancing research and development for integrating UAVs into cellular networks. An emerging testbed that will enable this research is the Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) [17].

AERPAW is one of the Platforms for Advanced Wireless Research (PAWR). It deploys advanced hardware and software in a city-scale outdoor environment for supporting research, development, and testing of emerging mobile communications networks. The AERPAW architecture, design, and deployment aim to enable a safe, reliable, and efficient platform for research and development. The role of a UAV in the testbed can be that of an aerial UE (AUE), aerial relay (AR), or aerial BS (ABS). Such aerial nodes in a testbed allow the investigation of different use cases, such as aerial handover, air-to-air and air-to-ground communications, aerial monitoring, and localization. These and other research opportunities are enabled by a modular SDR design and deployment [18].

In this paper, we provide the experimental data from field trials of cellular network-connected UAVs using fully open-source SDR solutions. These results show high throughput over hundreds of meters and different AUE heights served by a low-power ground BS and demonstrate the feasibility of deploying a modern cellular network for UAS communications research. Section II introduces the measurement procedure. Section III describes the experimental system, including the radio hardware, software, and computer network. Section IV presents the obtained radio link performance results with two popular 4G LTE software implementations that are 3GPP compliant, freely available, and supported by large user communities. Section V provides the concluding remarks and a research outlook.

## II. Measurement Procedure

The main objective of our testbed design is providing broadband wireless link connectivity between the AUE and ground BS using advanced wireless communications protocols. The initial step is the establishment of a wireless link between the AUE and ground BS. Next, we perform different measurements to validate the data transfer rate achieved between the ground and aerial radios. The AUE is an SDR carried by a COTS UAV that flies at various altitudes and follows different trajectories. For the purpose of gaining insights into the optimal choices and configurations of the hardware components, software libraries, wireless network parameters, and aerial node positions and trajectories, we perform multiple tests including indoor tests using radio frequency (RF) cables and over-the-air outdoor experiments. The purpose of this paper is to present our over-the-air experiments.

Most of the initial experiments can be summarized as follow: First, the wireless link between the LTE BS, or eNodeB (eNB), and the UE is established and verified against existing benchmarks while the UE is stationary on the ground and in close proximity without any control signals from the remote controller (RC). Then, the drone and RC are turned on and the aerial node takes off and flies to a set of latitude and longitude coordinates, for observing and capturing the achieved uplink (UL) and downlink (DL) data rates. Both the UE and the eNB use COTS SDR hardware and open-source software.

The procedure for the SDR experiment configuration applies to both the ground BS and the AUE and is carried out in three parts: parameter and experiment selection, profile configuration, and mapping of the profiles to the SDR equipment. The process starts by defining the different wireless configurations of the open-source library used to provide wireless communication capabilities, where the specific configuration will characterize the experiment. Specifically, the main parameters here are the UL-DL duplexing mode, UL and DL frequencies, the transmitter and receiver analog gains, and the the cellular system bandwidth. Moreover, custom RF chains, consisting of modular COTS RF components, need to be designed and attached to the transmitter and receiver for both the ground and aerial SDRs to accomplish the desired experiment in the outdoor environment.

## III. Hardware and Software Configurations

Leveraging the AERPAW framework and industry contributions, notably the Universal Software Radio Peripherals (USRPs) from National Instruments, we design the aerial and ground radio nodes for 3D cellular network experiments. Figure 1 illustrates the testbed architecture and design for the field experiments. The detailed description of each software and hardware component utilized in our setup is presented in the following subsections.

### *A. Hardware*

The SDR and RF hardware components are described in continuation. Fig. 2 illustrates our custom RF design for the transmitter and receiver of both radios, ground and aerial. The integration into the UAV node is captured by Fig. 3.

- **SDR Hardware:** SDRs are widely used for rapid prototyping and testing of a variety of waveforms and protocols, including 4G and 5G. An SDR is typically a general-purpose computer with a radio front end, or an embedded SDR platform that does not need a host computer. We use

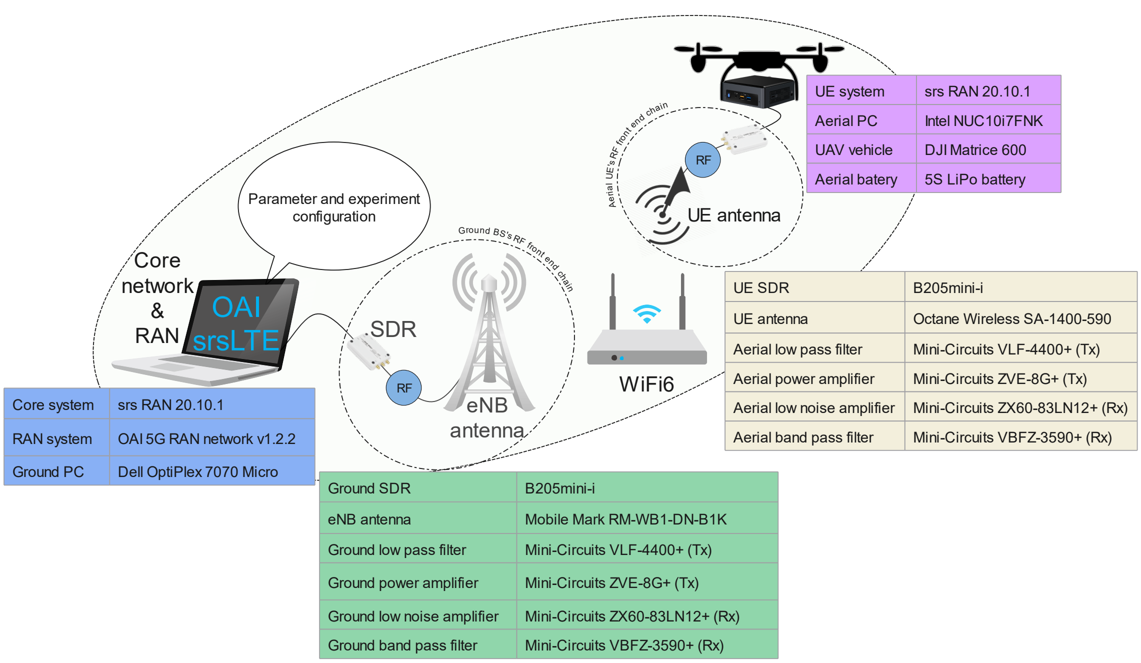

Fig. 1: The architecture and design of the testbed for field experiments.

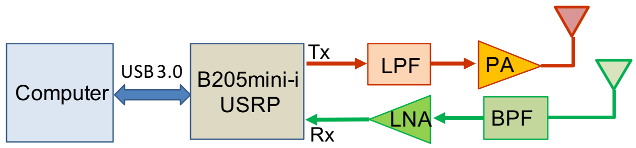


Fig. 2: The SDR and RF hardware chain of the ground and aerial experimental nodes.

dedicated SDR hardware to implement BSs and UEs with the corresponding software. The UE, which will be mounted on the UAV, must use an SDR that is small, lightweight, and have a low power demand to not significantly compromise the UAV flight mechanics. Therefore, a suitable SDR for the aerial node is the B205mini-i USRP [19]. The same USRP will initially be used at the ground node as well. The specifications of the B205mini-i SDR are as follows: up to 61.44 Msps sampling rate, up to 56 MHz instantaneous bandwidth, less than 10 dBm maximum transmit power, depending on the waveform, 0 dBm maximum permissible receiver input power, and a frequency range between 70 MHz and 6 GHz. The noise figure of the B205mini-i is specified as being less than 8 dB.

- **RF Front End:** The ground BS and aerial UE RF front ends are designed to operate in the 3.5 GHz range (3.3 GHz-4.2 GHz), which is part of the 5G spectrum. Our spectrum surveys showed no signals in Starkville, MS, in this band and an experimental license from the Federal Communications Commission (FCC) was obtained. The BS RF front end transmitter chain consists of a low pass filter (LPF) to attenuate possible harmonics, a power amplifier (PA), and a wideband and omnidirectional antenna. The front end of the BS receive chain has the same antenna, a bandpass filter (BPF), and a low noise amplifier (LNA). The aerial node uses the same components and architecture as the BS except for deploying smaller and lighter antennas. The detailed of all RF components are provided in continuation.

– **Antennas:** The BS antennas are Mobile Mark RM-WB1-DN-B1K that operate in the 617-960 and 1700-6000 MHz frequency ranges with 3 dBi peak gain. They can handle up to 10 W of power. These antennas cover nearly the entire 5G Sub-6 GHz frequency band and can also be used for NB-IoT and LTE-M applications. The aerial node's antenna model is SA-1400-5900 that is distributed by Octane Wireless and covers the frequency range from 1400 to 5900 MHz. This omnidirectional antenna has nearly no gain across the supported frequency range. The specified transmission power is up to 0.5 W.

– **Power amplifiers**: A PA is deployed in the transmit chain, and an LNA is used in the receive chain of both radios. The PA model is ZVE-8G+—with a heat sink on the ground node and without on the drone—from Mini-Circuits. It operates over a wide frequency range, from 2 to 8 GHz, has 30 dB minimum gain, and provides a maximum output power of 1 W. In the receiver chain, the ZX60-83LN12+ LNA, also from Mini-Circuits, has a wideband operating frequency between 0.5 and 8 GHz, which enables its use over the WiFi, LTE, S-Band radar, and C-band applications.

Fig. 3: The aerial node with the SDR and RF front end in the custom payload tray.

– **Filters:** Our design uses an LPF in the transmit chain and a BPF in the receive chain. The Mini-Circuits LPF VLF-4400+ operates from DC to 4400 MHz. The Mini-Circuits BPF VBFZ-3590+ has a passband range from 3000 to 4300 MHz with the center frequency at 3590 MHz. The BPF corresponds to a wideband band selection filter that covers the frequency range of interest in the 5G mid-band for AERPAW experiments, whereas the LPF is used to suppress harmonics at multiples of the local oscillator frequency.

- **Computers:** For the experiments presented in this paper, two computers are used. The ground node should be more powerful, so we use a computer with an Intel i9-9900 processor with eight cores. The aerial node computer needs to be lightweight and power efficient, while providing sufficient processing power for wideband signal processing. We therefore recommend the Intel NUC10i7FNK featuring an Intel i7-10710U processor with four cores. Multiple physical cores are important to efficiently implement 4G and 5G signal processing algorithms that can be parallelized and pipelined on an x86 processor to provide real-time communications at high data rates. Both computers run Ubuntu 18.04.3 LTS which is compatible with the software of interest. Ubuntu also provides a suitable environment for the USRP Hardware Driver (UHD) that is needed for interfacing with any USRP.
- **Networking:** Both the BS and aerial node computers are connected to a WiFi control network for the purpose of passing test results and control commands via secure shell (SSH). The network utilizes WiFi6, or 802.11ax, because it can operate in the 5 GHz band and has long range thanks to its multi-user multiple input, multiple output (MU-MIMO) capability. Note that the 2.4 GHz ISM band is used by the RC and the corresponding radio on the drone.

### B. Software

Various free open-source software development libraries have been the enablers for widespread experimental research on waveforms and protocols using COTS SDR hardware. The availability of open-source 4G LTE software for real-time over-the-air communications and the emerging 5G software development efforts continue driving wireless communications and networking research towards a full softwarization and virtualization of cellular communications networks. Two popular open-source software libraries for building 4G and 5G systems are srsLTE and Open Air Interface (OAI).

- **srsLTE** offers an open-source software library for implementing 4G LTE networks with SDRs. It implements the three main components of an LTE network: the UE, eNB, and evolved packet core (EPC). The srsUE provides features up to 3GPP Release 15, supporting both time and frequency division duplex (TDD and FDD). The srsENB currently supports the 3GPP Release 10 specifications. The srsEPC implements the basic functionalities of an LTE core network, including the mobility management entity (MME), home subscriber system (HSS), and the serving and packet data network gateways (S/P-GW). The software supports the standard LTE bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz and is compatible with COTS SDR hardware [20].
- **OAI** is an open source software project that allows simulation and experimentation with advanced wireless networks using SDRs. It implements the 4G LTE network in software. In 2017, OAI started the implementation of the 5G New Radio (NR) specifications. Currently, OAI supports 4G-5G dual connectivity with the required physical channels, employing low-density parity-check (LDPC) channel coding, among others. Reference [21] provides details of the currently supported features and road map of OAI.

Both the base station, containing srsLTE EPC and OAI eNB, and srsLTE UE are isolated from the rest of their systems by using Docker containers. Each container was configured using the privileged mode which gives the container access to all Linux capabilities and hardware devices. In this case, the capabilities of interest are NET_ADMIN for creating the EPC and UE interfaces and SYS_NICE for real-time scheduling. The privileged mode also gives the container access to USB devices such as the B205-i mini SDRs used in the experiments.

The default settings for srsLTE EPC and OAI eNB do not allow them to work together immediately. The configuration of one must be modified such that the public land mobile network values (PLMNs) and tracking area code (TAC) match between the EPC and the eNB. Additionally, the frequencies between the eNB and UE will need to match. In OAI, the frequency is chosen by selecting a band, downlink frequency, and an offset from the downlink frequency for the uplink. In srsLTE, the frequency is defined by the E-UTRA Absolute Radio Frequency Channel Number (EARFCN). The downlink frequency will be chosen based on the EARFCN value, and the uplink frequency will be automatically set as per the standard association for a given EARFCN.

## IV. Experiments and Results

We consider the DL and UL communications performance between the SDR BS and the SDR AUE. We use the OAI library to implement the eNB, and srsLTE to implement the EPC and UE, and consider 10 and 20 MHz LTE system bandwidths. Table.I describes the experimental setup and parameters. We use OAI version v1.2.2 as it is the latest stable version and srsLTE version 20.10.1 as it is the latest and provides improved throughput from previous versions.

TABLE I: The parameters of the AERPAW field experiments.

| **Experiment parameter** | **Value** |
|---|---|
| Test field area | 1000 m x 1000 m open field |
| eNB antenna height | 2.5 m |
| System bandwidth | 10 and 20 MHz |
| Uplink carrier frequency | 3489.9 Hz |
| Downlink carrier frequency | 3589.9 Hz |
| Transmit gain | 78 dB |
| Receiver gain | 60 dB |
| Noise floor | -110 to -105 dBm |
| Transmission mode | FDD |
| Transport-layer protocol | TCP |
| Packet size | 8000 bytes |
| Modulation scheme | 64/16/4QAM (adaptive) |
| UE authentication | XOR |
| Encryption algorithm | EEA0 |
| Aerial battery capacity | 3000 mAh |
| Aerial battery voltage | 18.5 to 21 V |
| SDR power requirements | 5 V |
| LNA power requirements | 12 V |
| Aerial NUC power requirements | 19 V |
| Aerial node weight | 2.2 kg |

We measure the throughput between the ground eNB and the AUE at multiple waypoints where the UAV will hover during the throughput measurement. Throughput measurements are performed using IPerf3 with TCP traffic. The experiment starts from a predefined reference point on the ground near the eNB. Next, the communications link with the UE is tested and the radio parameters are optimized. This includes adjusting the SDR-specific transmit and receive gains at the eNB and UE; these are the analog gain settings of the USRP's internal power amplifiers. Another check of the communications link is performed with the UAV motors and RC turned on and the UAV hovering near the eNB, a few meters above the ground. Once a suitable connection is confirmed, the UAV flies to the designated 3D positions where the DL and UL data rates are independently measured and reported using IPerf3.

For clarity, we plot throughput over horizontal distance and height of the UAV with respect to the RC, which is close to the BS antennas; a few meters away to avoid the strong RC signal from affecting the SDR receiver. On the UAV, the SDR antennas are placed about 60 cm away from the RC antennas due to physical space limitations on the small UAV. The transmit and receive antenna of each SDR are separated by 1.2 m to limit the power leaking from the Tx antenna into the Rx port of the USRP for performance and safety reasons. The 10 and 20 MHz experiments are conducted one after the other at each of the 19 waypoints. Therefore, for each bandwidth switch, the LTE network needs to be restart and the UE detaches and reattaches to the new cell. The reference point (0,0) is the location of the RC unit, near the eNB antennas. FDD is configured in paired spectrum at 3.5 GHz with 100 MHz frequency separation between the UL and DL. The B205mini-i USRP transmit and receive power gain

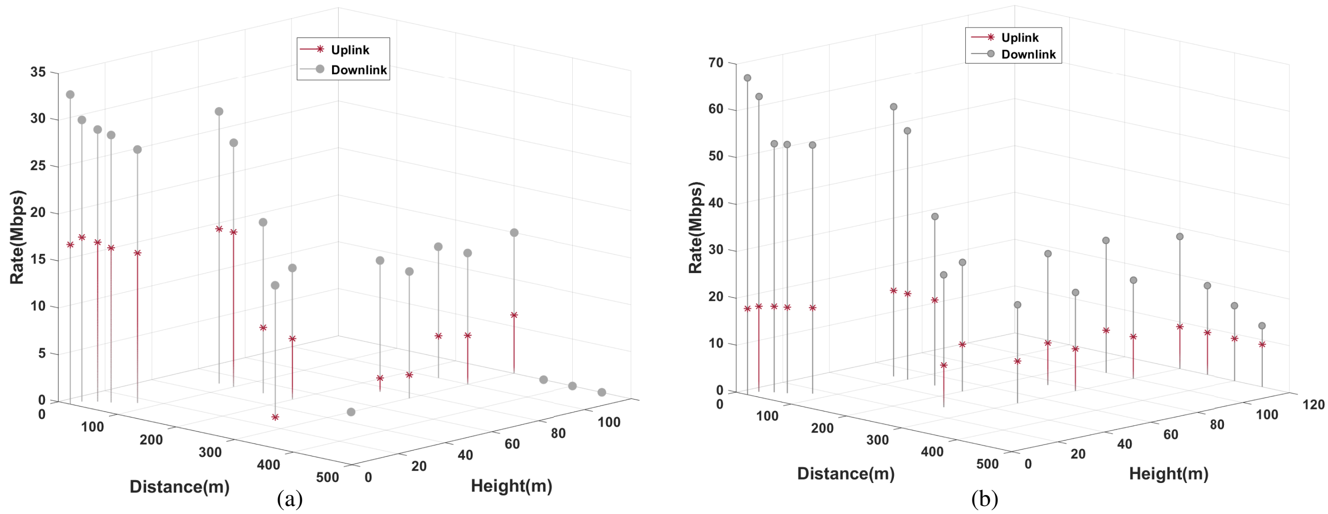

Fig. 4: Measured UL and DL data rates at 3.5 GHz for a 10 MHz (a) and a 20 MHz SDR LTE system (b).

is set to 78 and 60 dB on both the eNB and the UE SDR, respectively.

Figures 4(a) and 4(b) show the measured UL and DL data rates for system bandwidths of 10 and 20 MHz, respectively. Both figures show that the aerial-to-ground link achieves the highest rates when the AUE is close to the BS. The data rate gradually decreases as the UAV flies away from the BS. For the 20 MHz system, the highest measured rates are 68 Mbps for the DL and 19 Mbps for the UL. The measured rates at the same coordinates during the 10 MHz LTE experiment are 30 Mbps for the DL and 17.3 for the UL. Note that, although the UL LTE channel is 20 MHz, the scheduler at the eNB allocates only one half of the resources to the UE for its UL link, whereas all 100 resource blocks are allocated for the DL to the single UE. From these results, we observe that the communications link shows a robust throughput performance in line of sight over reasonable horizontal distances to the BS and AUE heights. When the UAV flies from 20 to 100 m horizontal distance with respect to the eNB, the throughput decreases from 68 to 53 Mbps for the 20 MHz system and from 30 to 26 Mbps for 10 MHz. After the UAV passes the 100 m horizontal distance, the throughput drops rapidly to one half and continues to drop as the UAV moves farther out. It is noted that the 10 MHz LTE system experiences zero throughput when the UAV is at greater horizontal distances and low altitudes. However, when increasing the UAV height, the link stability and data rate considerably improve. The omnidirectional antennas at the eNB and UE are vertically polarized, and due to ground reflections, the signal strength is good at short horizontal distances and higher altitudes. The maximum UAV height is restricted by the Federal Aviation Association to 120 m.

By comparing the results plotted in Fig. 4(a) and Fig. 4(b), we observe that the use of a wider system bandwidth improves the throughput proportionally to the radio resources and the reliability of the wireless link is also improved.

Figure 5 shows results with and without employing the LNA in the receive chain of each SDR. We notice that the non-LNA implementation cannot sustain the communications link in line of sight beyond 50 m horizontal distance. With the LNA, however, an improved throughput performance of 25-30 Mbps and 50-60 Mbps on the downlink for 10 and 20 MHz LTE, respectively, is maintained up to 100 m. Note that since the LNA increases the gain in the receive chain, one must pay attention to not saturate the receiver. This can be done through design and configuration. We use a bandpass filter and physically isolate the transmit and receive antennas of the SDR from one another and from the RC antennas. We also empirically evaluate suitable USRP Rx gains.

## V. Challenges and Future Research

During our design, development, and measurement campaigns we faced several challenges and we include a brief discussion of two of them below.

- **RF Interference:** The RC signal and the feedback from the UAV are high power and can stress and even saturate the USRP receiver when the signal source is close to the USRP receive antennas. It is therefore important to use filters and/or physical separation of antennas between the two radios, as well as between the the transmit and receive antennas of a single SDR.
- **Limited power:** After experimenting with USRPs without PAs and later with the 1 W amplifiers, we noticed a considerable signal strength improvement. We measured about 50 mW clean signal power at the PA output in the transmit chain and made sure that the leakage into the receiver was tolerable and did not significantly impact the performance. PAs are necessary for outdoor experiments with these SDRs beyond 50 m in ideal line of sight conditions, according to our measurements on the ground. But even with the 1 W PA, the throughput becomes low and the AUE detaches from the eNB when the UAV travels beyond 400 m distance from the

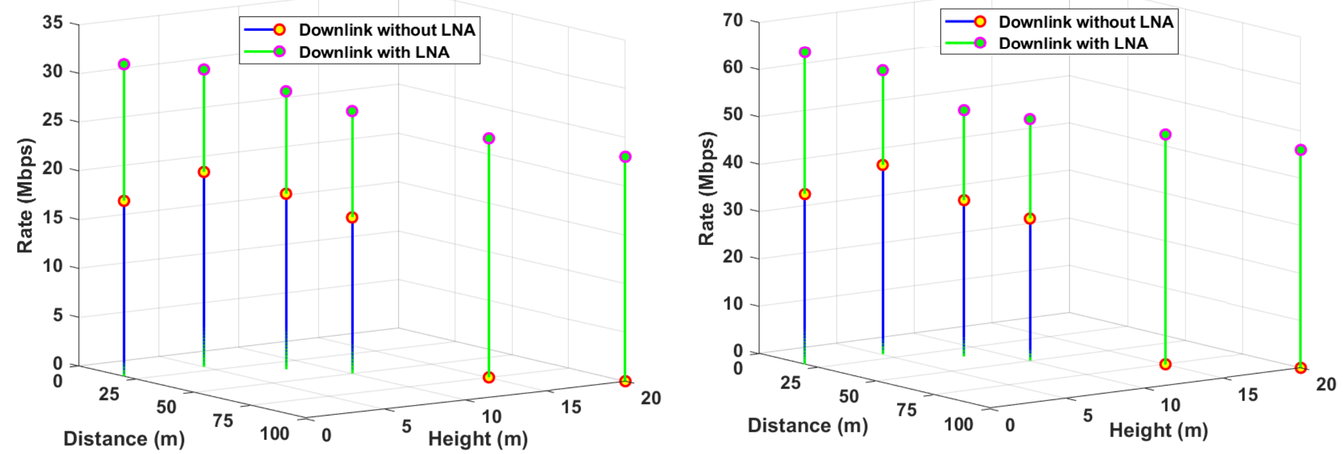


Fig. 5: Measured DL data rate at 3.5 GHz for a 10 MHz (a) and a 20 MHz SDR LTE system (b) with and without the LNA.

eNB. For longer ranges, higher transmit power or antenna gain, or operation at a lower frequency is necessary.

We plan to extend these trials with more experiments to investigate interference with other aerial and ground nodes, test handover from one to another cell, and collect data using an ABS and ground UE as well as aerial-to-aerial links.

## VI. Conclusions

While the concept of networked and cellular-connected UAVs is being standardized, researchers need a platform to prototype and test new technology. This paper describes early experiments of cellular-connected UAVs, where the cellular network and the users are fully software-defined and use COTS SDR, RF, computing, and networking equipment that is widely available. We provide detailed information about the SDRs, RF components, and open-source software used to successfully establish 4G LTE wireless links between the AUE and ground BS. The obtained results show that the throughput performance between aerial and ground radios is reliable, scalable, and robust. These results provide early insights about aerial coverage and how to experimentally evaluate 3D communications performance. The AERPAW testbed will provide a platform for wide area experimental research by deploying multiple cells, radios, and UAVs.

## Acknowledgement

This work was supported in part by the NSF PAWR program, under grant number CNS-1939334.

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