

# POWDER: Platform for Open Wireless Data-driven Experimental Research

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## ABSTRACT

This paper provides an overview of the Platform for Open Wireless Data-driven Experimental Research (POWDER). POWDER is a city-scale, remotely accessible, end-to-end software defined platform to support mobile and wireless research. Compared to other mobile and wireless testbeds POWDER provides advances in scale, realism, diversity, flexibility, and access.

## 1 INTRODUCTION

The wireless networks that we have today are clearly not the wireless networks that we need for the future. Significant advancements cannot be attained by tinkering around the edges of existing networks. To drive forward the science of wireless networking, we need innovative researchers to build their own networks at scale and in real environments, with control and visibility from the lowest layers of the radio up to the top of the application stack. I.e., we need a city scale wireless testbed. Since wireless devices are diverse and mobile, the testbed must be too; since technologies change rapidly (and sometimes unpredictably) at all layers of the stack, the platform must likewise be able to adapt to community needs to stay relevant. Such a living laboratory needs to be built with the precision of a scientific instrument so that experimenters can have confidence in the accuracy and reproducibility of their results, and must be built from the ground up to support the scientific process.

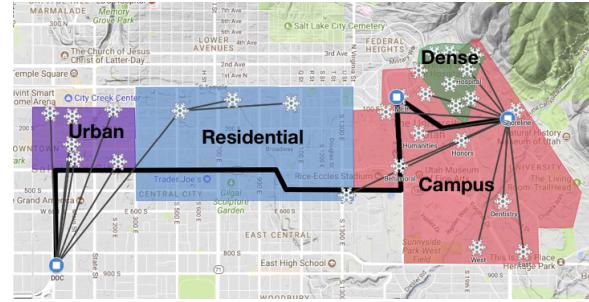
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**Figure 1: POWDER (planned) city-scale footprint, including a campus, residential, urban and dense deployments. Snowflakes represent “base stations,” blue circles with white squares are compute clusters, black and grey lines are front/back-haul fiber.**

It must support not only competition in the race for cutting edge technologies, but also cooperation and collaboration that enables researchers and industrial users to build on each others' work.

This is the vision that is driving the design and realization of the Platform for Open Wireless Data-driven Experimental Research (the **POWDER** platform) currently being deployed in Salt Lake City, Utah. I.e., POWDER is a **highly flexible city-scale scientific instrument that enables research at the forefront of the wireless revolution**. POWDER is a partnership between the University of Utah, Salt Lake City, and over a dozen other public and private organizations (local, national and global). POWDER is one of the platforms being developed as part of the National Science Foundation (NSF) Platforms for Advanced Wireless Research (PAWR) program. The PAWR program is a public-private partnership between the NSF and an industry consortium of more than thirty organizations.

Designing and realizing the POWDER living laboratory involves addressing many challenges, several of which have contradictory requirements. The challenges include finding practical answers to the following questions: How to support a broad range of research, the experimental needs of which are largely unknown? How to enable an experimental workflow environment that can support such a broad range of research? How to enable research for users who are not physically present at the testbed location? How to ensure experimental repeatability? How to ensure the longevity of the platforms? How to allow safe and compliant radio frequency (RF) transmissions in a real world environment with many other RF

services? How to enable multiple users at the same time, and yet prevent interference between experimenters? How to manage platform resources and tools to support many different configurations, without getting overwhelmed by operational complexity?

This paper describes the design and realization of the POWDER platform and the strategies we employ to address these challenges.

POWDER is deploying dozens of programmable radio nodes at fixed locations over an area of fourteen square kilometers, with approximately fifty mobile programmable radio nodes traveling through the area on couriers. This contiguous space covers three distinct environments: an urban downtown, a moderate density residential area, and a hilly campus environment. The physical deployment also offers a variety of configurable “coverage” scenarios, e.g., conventional macro-cell, or small-cell (enabled by the campus “dense” deployment), or combinations thereof (see Figure 1). Diversity in mobility is provided by using mobile couriers that have relatively predictable movement patterns (e.g., buses), less predictable but bounded mobility (e.g., maintenance vehicles), and couriers that are “controllable” (e.g., backpacks/portable endpoints that can be moved by researchers that come on-site). Each of the deployed nodes consist of user-programmable software defined radios (SDRs), off-the-shelf (OTS) radio equipment, RF front-ends and antennas. Each node is also designed to support a modular “bring-your-own-device” (BYOD) approach whereby experimenters can augment or “replace” functionality in the nodes. All POWDER nodes have out-of-band access so that experimenters can remotely control, monitor, and collect data from their experiments. Nodes also have modest local compute and storage capabilities (i.e., edge compute with sub-ms latency), and the ability to access large amounts of cloud computing capacity both in the metro area (with a few milliseconds of latency) and across the country. Fixed nodes deployed as base stations are connected with each other and compute resources via a dedicated fiber front-haul/back-haul network.

On top of this physical infrastructure, POWDER runs a sophisticated testbed control framework that has build-in support for complex device provisioning and a set of tools for scientific workflow management, collaboration, and artifact sharing. This framework must meet two seemingly contradictory goals: to *provide zero friction between experimenters and raw access to hardware* and to *make it simple for beginners and those who wish to run high-level experiments to get their work done*. Low-level access is necessary for the simple reason that this is where innovations in core wireless communication happen. At the same time, many users, such as those working on wireless service level architectures, for example, don’t need to reprogram radios, and are better served by platforms that provide them higher levels of abstraction. The POWDER control framework [25] provides these features. POWDER “profiles” allow one experimenter to run directly on raw hardware, e.g., to explore new wireless waveforms or spectrum management technologies, and another to run a higher-level framework, such as the open network automation platform (ONAP) ([www.onap.org](http://www.onap.org)), or a complete end-to-end 5G mobile network, on the same platform with equal ease.

POWDER supports a broad range of research areas, including: *Architecture* of next-generation wireless networks (taking advantage of POWDER’s deeply programmable radio, switching and compute resources to explore novel designs in wireless data); strategies for

*Dynamic Spectrum access*, using available bands over a wide range of spectrum by flexibly monitoring and adapting to RF conditions, and exploiting our wideband antennas and SDR transceivers; *Network Metrology* through the measurement of wireless network performance and behavior under varied conditions, throughout the enormous combinatorial space of our multiple locations, flexible hardware, available frequencies, fixed and mobile stations, etc.; and *Applications/Services* with deep end-to-end programmability supporting almost all conceivable application and service models throughout wireless and core networks ranging from lightweight application software on OTS consumer UEs to intensive centralized high-performance computation on our data center resources.

We describe related work in §2. A more detailed description of POWDER is provided in §3. The POWDER hardware building blocks and example use cases (for which there are existing profiles available) are described in §4. A summary of the current POWDER deployment status is provided in §5.

## 2 RELATED WORK

To our knowledge, there is no existing city-scale outdoor testbed which provides the scale, flexibility and varied scenarios, or which enables the design and evaluation of future networking systems, in the way POWDER does. The fact that POWDER is remotely accessible and open to outside researchers also differentiates it from many earlier testbed efforts.

In terms of indoor wireless testbeds, the ORBIT testbed has been an early and unique resource, enabling wireless research by providing access to stationary nodes deployed in a relatively small area [18]. More recent indoor testbeds include Arena [3] and the Drexel Grid SDR testbed [7]. Another US-based indoor testbed is the PhantomNet controlled RF environment [2], which is being refreshed and integrated into POWDER. In Europe, Fed4Fire+ ([www.fed4fire.eu](http://www.fed4fire.eu)) federates a number of testbeds, including a number of indoor wireless facilities: w-iLab.t is an indoor wireless testbed with a variety of wireless equipment (sensor nodes, WiFi and LTE equipment) ([doc.ilabt.imec.be](http://doc.ilabt.imec.be)). The IRIS ([iristestbed.eu](http://iristestbed.eu)) and NITOS ([nitlab.inf.uth.gr/NITLab/nitos](http://nitlab.inf.uth.gr/NITLab/nitos)) testbeds provide software defined radios in an indoor environment (similar in functionality to ORBIT). The R2lab is a wireless testbed within an anechoic chamber with OTS and SDR wireless devices ([r2lab.inria.fr](http://r2lab.inria.fr)). The TRIANGLE project provides 5G application and device benchmarking capabilities ([www.triangle-project.eu](http://www.triangle-project.eu)). These indoor wireless testbeds do not have the scale and real world conditions available in POWDER.

Earlier US-based outdoor testbeds include DOME [23], CORNET ([cornet.wireless.vt.edu](http://cornet.wireless.vt.edu)), OpenRoads [26], CorteXlab [16], ORBIT outdoor, and Microsoft’s campus bus WLAN service [6]. In Europe the Fed4Fire+ federation includes a number of outdoor wireless testbeds, including: CityLab, a “neighborhood level” smart city testbed ([doc.lab.cityofthings.eu](http://doc.lab.cityofthings.eu)) with WiFi and IoT equipment and an outdoor instance of NITOS (supporting WiFi, WiMAX and LTE). These earlier outdoor testbeds often lacked the flexibility available in indoor facilities, were relatively small in scope and were typically focused on providing access to specific wireless technologies, e.g., 3G, LTE, WiMax, and WiFi. Several of the earlier outdoor testbeds

also were not open to outside researchers. In contrast, POWDER provides a highly flexible end-to-end software defined infrastructure, at city-scale and is open to external researchers.

Recent European efforts also include 5G specific experimental infrastructures, such as 5G-VINNI ([www.5g-vinni.eu](http://www.5g-vinni.eu)) and 5GENESIS ([5genesis.eu](http://5genesis.eu)). These infrastructures are focused on 5G specific experimentation with significant industry involvement and using commercial equipment. As such they support a different set of research questions than POWDER, e.g., research associated with application performance or measurements of commercial wireless environments.

The POWDER “sister” projects under the Platforms for Advanced Wireless Research (PAWR) umbrella ([advancedwireless.org](http://advancedwireless.org)), are closely related to POWDER and share some of the same high-level objectives. The COSMOS platform has a similar high level architecture as POWDER, but with smaller footprint and a specific focus on mmWave technologies [19]. AERPAW is a more recent PAWR platform with a focus on aerial wireless communication ([aerpaw.org](http://aerpaw.org)).

### 3 POWDER PLATFORM OVERVIEW

The POWDER architecture is directly driven by current and emerging research needs, and is ready to evolve over time as research questions change. To understand our design, it is helpful to think of it as having three major components: the **physical infrastructure** out of which the facility is built, the **functionality** that infrastructure is designed to provide, and the **control framework** that manages the facility and provides services to users. *Flexibility* and *diversity* are built into the platform at all three levels. The physical infrastructure includes a variety of different types of radios, antennas, environments, and mobility patterns. It is designed so that both general-purpose and specialized equipment can coexist side-by-side, and that BYODes can be added by experimenters. The functionality enabled by these devices is designed to maximize research impact by providing deep programmability end-to-end: from SDRs in the mobile devices and base stations all the way through edge and metro cloud compute platforms. A collection of hardware does not, by itself, constitute a platform for experimentation, so we need a control framework to provision, monitor, and configure the equipment and to provide services to users. By using a control framework that exposes devices at a very low level, users’ access to the devices is unfettered, enabling the diversity that will be required to support the large investment in wireless research that is expected in the upcoming years.

#### 3.1 Physical Infrastructure

An overview of the physical architecture of the POWDER platform is shown in Figure 2. When fully deployed, POWDER will have dozens of *base stations*<sup>1</sup> (#1 in Figure 2) on the UofU campus, in the downtown Salt Lake City area, and in a residential area connecting the two. Different areas of the deployment have different densities of base stations. Specifically the UofU campus will have both rooftop base stations as well as more densely deployed base stations at

<sup>1</sup>The functionality of an SDR is determined by the software executing on it. As such, with the appropriate software *any* SDR can act as a base station, or a wireless endpoint, or a wireless measurement node etc. Nevertheless, for ease of exposition, we use generic wireless terminology, i.e., base station, endpoint etc., to describe the POWDER architecture.

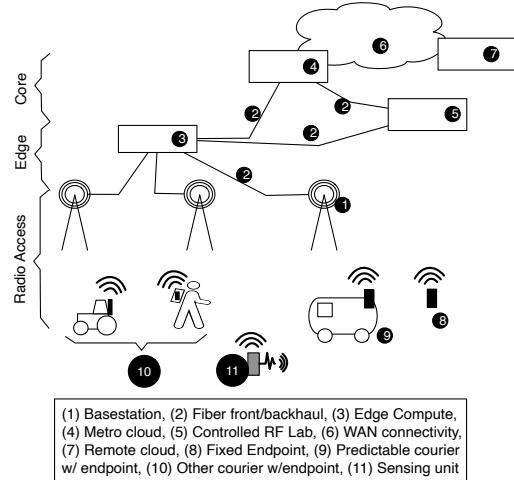


Figure 2: POWDER Overview

“street level.” (See Figure 1.) This diversity gives experimenters a range of environments and possible configurations in which to run their experiments.

POWDER has two types of base stations. *General purpose base stations* consist of a number of OTS SDRs, an RF front end and antennas, and a complement of control hardware for managing and accessing the devices. (Out-of-band access is provided via the fiber infrastructure described below.) Specialized *massive multi-input multi-output (mMIMO) base stations* consist of SDRs and antennas in a dedicated configuration to support mMIMO research.

All base stations are fronthauled/backhauled using a dedicated fiber infrastructure (#2) to an *edge compute cluster* (#3). The edge compute cluster consists of a rack of general purpose compute and storage servers, within 60 µs round-trip-time of the base stations. The compute nodes at the edge compute cluster provide the compute needs of base station SDRs. The edge compute locations are also network aggregation and connection points to the *metro compute platforms* (#4), using 100 Gb/s links. In POWDER these metro compute platforms are the existing Emulab cluster ([www.emulab.net](http://www.emulab.net)) on the UofU campus and the CloudLab clusters ([www.cloudlab.us](http://www.cloudlab.us)) in the UofU downtown datacenter. These clusters are within a millisecond of all base stations. POWDER also connects to, and is federated with, our existing wireless and mobile testbed PhantomNet [2] (#5). PhantomNet provides wireless experimentation in a controlled RF environment, i.e., RF equipment in Faraday cages are interconnected via a software-controlled attenuator matrix. This federation with PhantomNet allows for experiments to be smoothly moved back and forth between a controlled laboratory environment (PhantomNet) and the POWDER living lab. As shown in Figure 2, together with the other testbeds at the UofU, POWDER connects to Internet2 (#6) to allow federation with other platforms: such as the CloudLab sites at Clemson and Wisconsin (#7) and the GENI “edge cloud” ecosystem. POWDER will also be connected to the programmable national footprint FABRIC infrastructure ([fabric-testbed.net](http://fabric-testbed.net)).

The full POWDER deployment will have close to fifty *wireless endpoints* (#8-10). Wireless endpoints have a similar basic configuration as the general purpose base stations (i.e., SDRs, RF front end and

antennas and control infrastructure). They differ from base stations in two regards: Out-of-band access is provided by commercial LTE modem or WiFi (when devices are in range of the UofU campus network), and the computing needs of the endpoint SDRs are provided by small-form-factor compute nodes co-located with the endpoint. Some of the wireless endpoints are deployed at human height at *fixed locations* (#8). Other wireless endpoints will be deployed on a variety of mobile “couriers.” There will be two types of couriers: those that can realize *predictable mobility* (#9) and couriers for *uncontrolled mobility* (#10). The predictable couriers are campus shuttles, of which the UofU maintains a large fleet with a variety of on- and off-campus routes. Uncontrolled couriers include localized vehicles (i.e., campus and city owned vehicles that stay within our coverage zones, such as snow plows, lawn mowers, street sweepers etc.). Finally, POWDER will have dozens of IoT sensor units (#11). The sensor units will be deployed both alongside mobile endpoints, and in static locations throughout our proposed wireless coverage area.

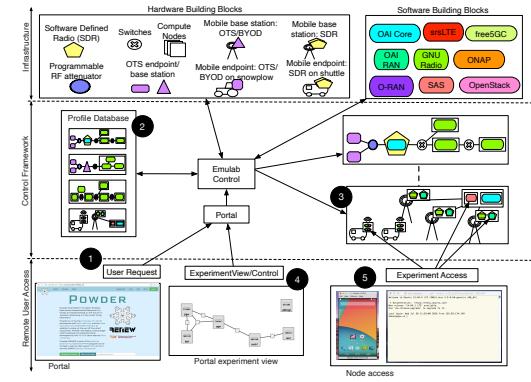
### 3.2 Functionality

**General Purpose Functionality.** The physical infrastructure described above becomes **hardware building blocks** in POWDER. As shown in Figure 3, these hardware building blocks are combined with a variety of **software building blocks** as well as the POWDER **control framework** to realize the overall functionality of the POWDER infrastructure. Using the POWDER control framework (described below in more detail) allows these hardware and software building blocks to be composed into meaningful experiments in the platform.

POWDER software building blocks include a variety of SDR stacks (such as GNU Radio ([gnuradio.org](http://gnuradio.org)), OpenAirInterface ([openairinterface.org](http://openairinterface.org)), and srsLTE ([github.com/srsLTE](https://github.com/srsLTE))), core mobile networking stacks (such as free5GC ([free5gc.org](http://free5gc.org)), and OpenAirInterface Core, RAN virtualization/programmability stacks (such as O-RAN ([www.o-ran.org](http://www.o-ran.org))), as well as general purpose network virtualization and cloud computing stacks (such as OpenStack ([openstack.org](http://openstack.org)), ONAP ([onap.org](http://onap.org)), and XOS/CORD ([opennetworking.org](http://opennetworking.org))). The result is that the entire system—endpoints, base stations, networks, and cloud computing infrastructure is software-defined.

The radio equipment in base stations and endpoints is designed to provide wide frequency capability, to provide experimenters with maximum flexibility in selecting propagation characteristics, spectrum licensing authorizations, avoiding interference, and interoperability with existing equipment. Each radio can be allocated to different experimenters, (assuming they operate in non-overlapping spectrum bands), thus allowing multiple experiments to use the same part of the platform concurrently. Alternatively, all radios might be allocated to one experiment where a researcher might use one for the “active” experiment, one for passively monitoring the experiment, and a third for providing frequency interference.

**Special Purpose Functionality.** For **extended and customized functionality**, the base stations and mobile endpoints can be expanded with specialized equipment for experiments that cannot be run on the OTS SDRs, such as OTS endpoint equipment (e.g., smartphones or IoT device), BYOD equipment built by experimenters, or



**Figure 3: Functionality and Experimental Workflow**

specialized devices built by the PAWR industry consortium members. This equipment can use the same control and network infrastructure as the general-purpose SDRs.

As described earlier, specific special-purpose functionality available in POWDER is programmable mMIMO equipment and open source software. The mMIMO equipment derives from the Argos [22] mMIMO technology developed by Rice University and now being commercialized by Skylark Wireless. The mMIMO open source software is being provided by the POWDER “companion project” RENEW (Reconfigurable Eco-system for Next-generation End-to-end Wireless) ([renew.rice.edu](http://renew.rice.edu)).<sup>2</sup>

### 3.3 Control Framework

The POWDER control framework is based on the Emulab control framework ([www.emulab.net](http://www.emulab.net)). Emulab provisions at an extremely low layer, giving researchers direct access to hardware (as opposed to virtualized or container-based frameworks)—a critical feature for cutting-edge communications design and for systems with real-time requirements. A principal goal of the framework is to provide *zero penalty for remote access*: that is, to make as many features available to remote users as possible so that they can work just as effectively as if they were on-site. In addition to managing user access, experimental resource allocation and experimental control, it provides a *profile* abstraction and support for *scientific workflows*. Profiles capture the relationships and dependencies between building blocks (both hardware and software) making them a key enabler for several important features. First, profiles provide the “recipes” with which the POWDER software and hardware building blocks are combined and instantiated into meaningful end-to-end experiments. Through its profile mechanism POWDER provides a set of functional “one click” experiment environments for popular stacks such as OpenAirInterface and srsLTE for 4G and 5G networks, O-RAN for RAN virtualization and programmability, ONAP for network management, control and orchestration etc. Experimenters can create and share their own profiles, boosting scientific collaboration and repeatability. Second, profiles make it easy to support a range of users, from novices through the foremost experts in the world.

<sup>2</sup>POWDER and RENEW are funded as one project from an NSF perspective, the POWDER-RENEW project. POWDER is the platform described in this paper. RENEW involves the development of open source software for the Skylark Wireless mMIMO equipment.

Novices can get started using profiles that provide fully functional end-to-end experiments, enabling them to start working right away. Experts can use profiles that provide “raw” access to the equipment: for example, profiles that contain the tools to program SDRs, a task that they would do themselves.

Another valuable property of our control framework is its built-in notions of experiment life cycle and its ability to support sophisticated scientific workflow tools. The language used to describe profiles makes it straightforward to create “parameterized” experiments, enabling experimenters to run different versions of experiments or to do parameter sweeps. For example, starting small and scaling up once an experiment has been shown to work at a small scale, or running repeated trials using the same software but radios in different locations. Profiles are version controlled, meaning that researchers can go “back in time” to run previous versions of their experiments, asking questions such as “are my new results different because of changes to my experiment, or due to external factors?” When publishing results, researchers can also point to the specific version used to gather those results.

The numbered sequence in Figure 3 depicts the interaction between POWDER components as part of a typical user experimental workflow. Specifically:

(1) Users access the POWDER platform via a portal which, from a user perspective, embodies all aspects of the platform. (2) A user typically selects a profile as the first experimental step. POWDER provides a profile “database,” i.e., existing profiles provided by the platform team or created by users. Profiles describe the hardware and software building blocks that will be used to instantiate an instance of the profile. (3) Once the user has selected (and optionally provided parameters associated with the profile), the POWDER control framework takes over to instantiate an instance of the profile. (This includes: (i) Verifying that the profile is syntactically correct. (ii) Determining whether the requested resources, hardware and software, are available. (iii) Allocating the necessary resources for the user. (iv) Loading appropriate software (e.g., operating system images and other profile specific software) on the selected hardware resources. (v) Performing any additional configuration, e.g., network configuration to finalize the profile instance.) (4) While the profile is being instantiated the status of the process and details of the resources selected for the experiment is available to the user via the POWDER portal. (5) Once the profile is fully instantiated (an *experiment* in POWDER parlance), the user can access resources in the experiment via the portal. (E.g., by “ssh-ing” into nodes.)

## 4 POWDER BUILDING BLOCKS

### 4.1 Hardware

**General Purpose Base Station:** The general purpose base station components are shown in Figure 4. Experimental equipment includes four networked SDRs (two NI N310s and two X310s), an RF front-end (supporting frequency division duplex (FDD) and time division duplex (TDD)) and signal amplification. Three of the SDRs are connected to a banded Commscope antenna (VVSSP-360S-F). The fourth SDR is connected to a Keysight broadband antenna covering 20 MHz - 6 GHz (N6850A). The experimental SDRs’ 10 Gbps Ethernet links connect to a coarse wavelength division multiplexing (CWDM) multiplexer/demultiplexer (fs.com FMU-C182761M),

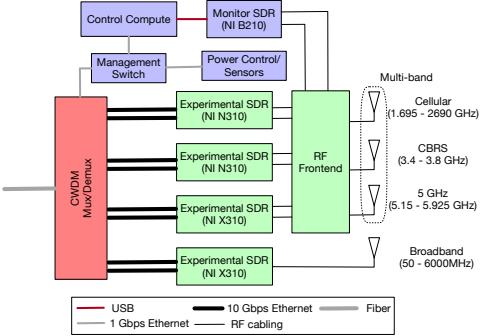


Figure 4: General purpose base station

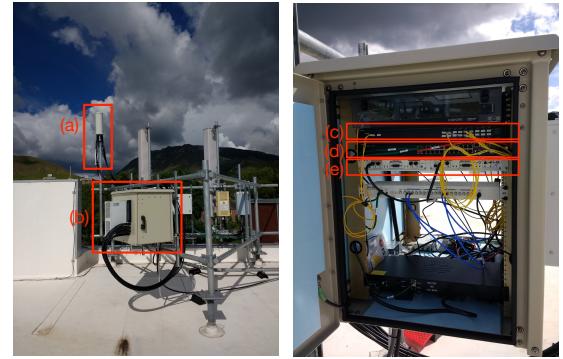
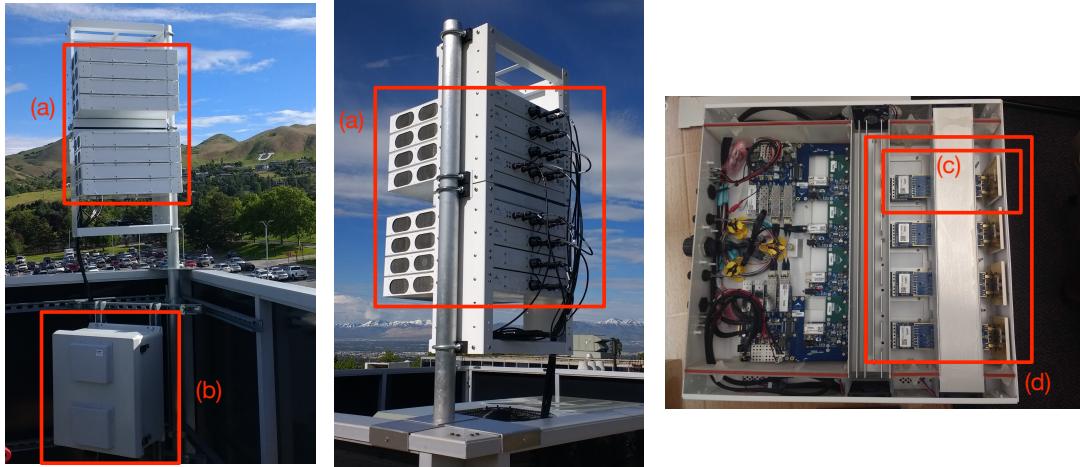


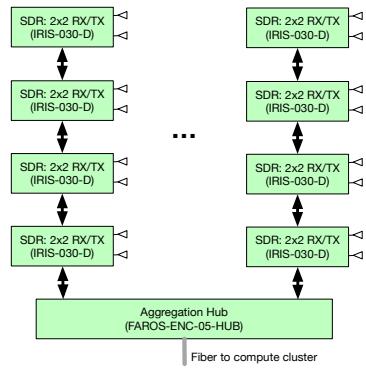
Figure 5: General purpose base station: (a) Multi-band and broadband antennas, (b) Enclosure, (c) CWDM Mux/Demux, (d) Management switch, (e) Experimental SDRs

which is connected via a private fiber run to a complementary CWDM mux/demux unit at the edge compute cluster which provides general purpose compute capabilities for the SDRs. (The SDRs also contain field programmable gate array (FPGA) functionality which enables radio-local processing.) The base station also contains an NI B210 monitoring SDR which is coupled to the transmit (TX) path of the experimental SDRs (via the RF front end). This allows monitoring [24] of the experimental SDRs to ensure Federal Communications Commission (FCC) compliance. The remainder of the base station equipment involves a small-form-factor control compute node (which is also the compute node for the monitoring SDR), a management switch and a variety of power control and sensors. As shown in Figure 5, the base station is housed in a climate controlled enclosure.

**Massive MIMO Base Station:** Figure 7 depicts the components of the mMIMO base station [21]. The array is built up of two transceiver SDRs (Skylark IRIS-030-D) that are interconnected to form a chain of SDRs. The SDR chains in turn are connected to an Aggregation Hub (Skylark FAROS-ENC-05-HUB) which serve to interconnect the chains and acts as an aggregation and connection point to the compute platform that gets paired with the base station for mMIMO operation. The base station configuration used in POWDER has four two-transceiver SDRs per chain and eight chains connected to the hub, making a 64-transceiver mMIMO base station. (See Figure 6.) As shown in Figure 6, each of the two-transceiver SDRs are front-ended by an RF front end and dual-polarized antenna

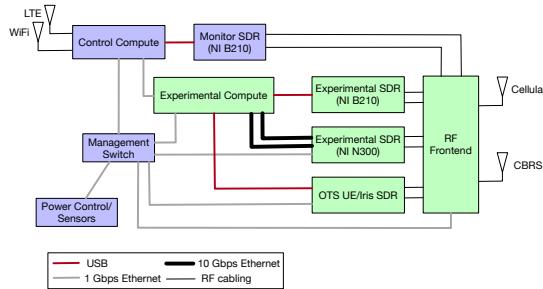


**Figure 6: mMIMO base station: (a) Radio and antenna array, (b) Hub, (c) 2x2 Transceiver and antenna, (d) Transceiver chain**



**Figure 7: mMIMO base station (Skylark Wireless)**

element (The Powder configuration is a broadband radio service (BRS)/citizens broadband radio service (CBRS) front end (Skylark IRIS-FE-03-CBRS) capable of operating from 2555 to 2655 MHz and from 3550 to 3700 MHz.)



**Figure 8: Endpoint base design packaged in different configurations: fixed endpoints, mobile endpoints and portable endpoints.**

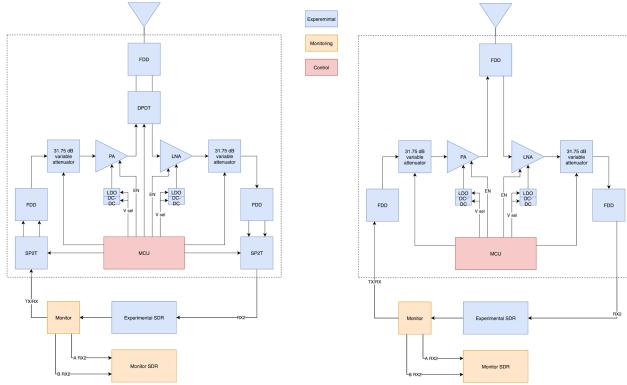
**Endpoint:** Figure 8 shows the base Powder endpoint design, which is realized on the platform in a number of different configurations, i.e., fixed endpoints, mobile endpoints and portable



**Figure 9: Fixed endpoint & mobile endpoint on campus bus**

endpoints. Like the general purpose base station, the main experimental components are SDRs, an RF front end and antenna elements. Endpoints may also include OTS endpoint equipment, e.g., smartphones. (Access to OTS devices is provided via Android Debug Bridge (ADB), which enables user interface access through software such as Vysor ([www.vysor.io](http://www.vysor.io)).) Because they lack high capacity fronthaul/backhaul networks, the experimental compute needs of endpoints are provided by co-located compute elements. Out-of-band access to endpoints is provided via WiFi or commercial LTE. Like the base station design, endpoints have a monitoring SDR (NI B210), coupled to the RF transmission/reception path, to ensure FCC compliance, and control and management elements. Powder fixed endpoints contain two NI B210 experimental SDRs combined with two Intel NUC small-form-factor compute nodes. Some fixed endpoints have OTS smartphones and others have Skylark Iris SDRs (for interworking with the mMIMO system). Mobile endpoints contain an NI B210 and NI N300 experimental SDRs, a Xeon-D Mini Server compute node and either OTS endpoint or Iris SDR. Endpoints are equipped with omni-directional wideband antennas (Taoglas GSA.8841 wideband I-bar). Mobile endpoints export their GPS coordinates via a near-real-time interface. (Figure 9 shows example fixed endpoint and mobile endpoint deployments.) Powder portable endpoints are designed to be used by experimenters who are physically present at the Powder platform and want to position the endpoint in a specific manner (e.g., put it in a specific

location, or drive along a specific route). Alternatively, the portable endpoints might be used by experimenters who want to bring their own endpoint devices to interact with the platform, but still have “normal” POWDER out-of-band access and experimental control. As such the portable endpoints are being designed to have the same basic access and control features as fixed/mobile endpoints, but to be more configurable in terms of the actual equipment they contain.



**Figure 10: RF front end: (a) Endpoint, (b) Base station**

**RF Front End:** Figure 10 shows the current revision of the front end, which provides LTE Band-7 communication. It provides frequency division duplexing functionality with uplink from 2500 to 2570 MHz and downlink from 2620 to 2690 MHz. Both base station and endpoint front ends are nearly identical in design in this revision. The only difference is that the endpoint has a double pole double throw (DPDT) switch on the frequency domain duplexer (FDD) to provide selection of transmitting on the uplink or downlink frequencies and the base station is hard wired to transmit on the downlink. Power amplification is the primary component that improves performance. A digitally step attenuator is used to protect the power amplifier from the maximum output power of the SDR it is connected to. The total transmitter gain is about 10-20 dB depending on the radio, tuned to allow saturation of the power amplifier by the SDR without causing damage. On the receive side we use a Low Noise Amplifier (LNA) tuned to the 2500 to 2700 MHz range. There is another digital step attenuator, after the LNA on the receive path, used for gain control. On both the receive and transmit paths a duplexer is connected between the amplifier and the attenuator to provide additional filtering. Finally, a network connected microcontroller (MCU) is used to monitor and control the system. It monitors temperature, voltage and current and controls power voltage per amplifier, bias current of the LNA, attenuators and enables/disables the PA.

## 4.2 Software & Example Use Cases

POWDER provides low level access to the hardware building blocks described earlier and as such enables a broad range of research without “getting in the way” of platform users. This is clearly a platform strength, i.e., researchers can combine the hardware building blocks in any way they see fit and use any software to realize their research. POWDER is, however a complex environment and this inherent flexibility can be overwhelming to users.

To mitigate this complexity, and to illustrate the range of areas/use cases POWDER supports, we use the *profile* mechanism described earlier to “package” hardware and software building blocks to creating starting points for a range of research [11]:

**RF monitoring:** The SDRs deployed in POWDER provide an ideal platform for monitoring RF transmissions in a real world environment. RF monitoring is receiving renewed interest because of efforts related to dynamic spectrum sharing [10], sharing between licensed and unlicensed spectrum use [9] and in general efforts related to innovative use of spectrum (e.g., FCC designated Innovation Zones<sup>3</sup> [8], exploration of radio dynamic zones [14] etc.) POWDER provides profiles that associate compute and radio equipment, and loads GNU Radio tools ([www.gnuradio.org](http://www.gnuradio.org)) to bootstrap this type of work.

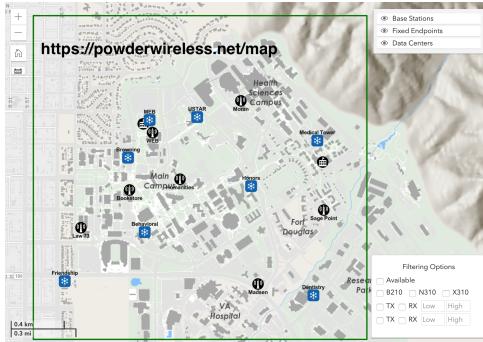
**Wireless communication:** The same low-level access to SDR hardware and software enable wireless communications research. For example, research associated with novel waveforms [17] and coding techniques [20], RF propagation modeling [1], novel wireless architectures [12] etc. The POWDER mMIMO system and software ([renew.rice.edu](http://renew.rice.edu)) is packaged in a POWDER profile and provides the means to explore questions specific to the coherent use of a large number of antennas and specifically to verify theoretical analyses related to the spectral efficiency of these systems [15]. POWDER also support the examination of numerous practical mMIMO issues, such as the implementation and overhead of pilot signals [13], coding strategies, and initialization procedures for adding users [4].

**Mobile communication:** The ability to flexibly combine POWDER RF resources with networking and compute resources in the platform enable a broad range of research related to mobile communication. We have numerous profiles associated with open source mobile networking software stacks that provide 4G and 5G functionality, (e.g., srsLTE and OpenAirInterface). The profiles associated with these stacks can be executed in over-the-air configuration, or using the POWDER controlled RF environment, or using simulated RF communication, thus enabling a range of research configurations [5]. The POWDER profile mechanism can also support sophisticated configurations/topologies associated with network function virtualization and orchestration, technologies that feature strongly in emerging network architectures, including 5G. For example, the POWDER ONAP profile automates the instantiation of this sophisticated industry standard management and orchestration platform. Finally, emerging efforts associated with “opening up” the RAN, and making those systems more programmable, is also readily supported with POWDER’s flexibility and unique mix of resources. POWDER specifically provides a profile of the emerging O-RAN ecosystem ([www.o-ran.org](http://www.o-ran.org)).

## 5 CONCLUSION AND POWDER STATUS

The Platform for Open Wireless Data-driven Experimental Research (POWDER) is a unique city-scale, remotely accessible, end-to-end software defined platform supporting a broad range of wireless and mobile related research. POWDER is operational and available for research and is, at the same time, still undergoing development as

<sup>3</sup>POWDER is an FCC Innovation Zone.



**Figure 11:** “Live” map of current POWDER deployment

we add features and capabilities and build out across all the full footprint. Figure 11 shows a screenshot of (and the URL for) a live map showing the current POWDER deployment. Table 1 provides a summary of the current deployment status and plans as of July 2020.

**Table 1: POWDER Status & Plans: July 2020**

Area: Functionality	Status	Notes
UofU Campus: Rooftop base stations	Deployed	8 deployed, 1 in progress
UofU Campus: Fixed endpoints	Deployed	7 deployment, 2 in progress
UofU Campus: Front/back-haul & edge cluster	Deployed	CWDM + 19 compute nodes
Metro Cloud (Campus/downtown datacenter)	Deployed	1200+ Emulab/CloudLab nodes
UofU Campus: Mobile endpoints	In progress	2 deployed, 26 in progress
Portable endpoints	In progress	Being prototyped
UofU Campus: Dense deployment	In progress	Deployment expected Q4 2020
SLC Downtown: Rooftop base stations	Planned	Expected Q3 2021
SLC Residential: Rooftop base stations	Planned	Expected Q4 2021

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## REFERENCES

- [1] Christopher R. Anderson and Gregory D. Durgin. 2017. Propagation Measurements and Modeling Techniques for 3.5 GHz Radar-LTE Spectrum Sharing. In *2017 32nd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*. <https://doi.org/10.23919/URSIGASS.2017.8105186>
- [2] Arijit Banerjee, Junguk Cho, Eric Eide, Jonathon Duerig, Binh Nguyen, Robert Ricci, Jacobus Van der Merwe, Kirk Webb, and Gary Wong. 2015. PhantomNet: Research Infrastructure for Mobile Networking, Cloud Computing and Software-Defined Networking. *ACM GetMobile* 19, 2 (April 2015), 28–33. <https://doi.org/10.1145/2817761.2817772>
- [3] Lorenzo Bertizzolo, Leonardo Bonati, Emrecan Demirors, and Tommaso Melodia. 2019. Arena: A 64-Antenna SDR-Based Ceiling Grid Testbed for Sub-6 GHz Radio Spectrum Research. In *ACM WiNTECH proceedings* (Los Cabos, Mexico) (*WiNTECH '19*). Association for Computing Machinery, New York, NY, USA, 5–12. <https://doi.org/10.1145/3349623.3355473>
- [4] Emil Björnson, Erik G. Larsson, and Mérourane Debbah. 2016. Massive MIMO for Maximal Spectral Efficiency: How Many Users and Pilots Should Be Allocated? *IEEE Transactions on Wireless Communications* 15, 2 (February 2016), 1293–1308. <https://doi.org/10.1109/TWC.2015.2488634>
- [5] L. Bonati, S. D’Oro, L. Bertizzolo, E. Demirors, Z. Guan, S. Basagni, and T. Melodia. 2020. CellOS: Zero-touch Softwarized Open Cellular Networks. *Computer Networks* 180 (24 October 2020), 1–13.
- [6] Ranvee Chandra, Thomas Moscibroda, Paramvir Bahl, Rohan Murty, George Nychis, and Xiaohui Wang. 2011. A Campus-Wide Testbed over the TV White Spaces. *ACM SIGMOBILE Mobile Computing and Communications Review* 15, 3 (November 2011), 2–9. <https://doi.org/10.1145/2073290.2073292>
- [7] K. R. Dandekar, S. Begashaw, M. Jovicic, A. Lackpour, I. Rasheed, X. R. Rey, C. Sahin, S. Shaher, and G. Mainland. 2019. Grid Software Defined Radio Network Testbed for Hybrid Measurement and Emulation. In *2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*. 1–9.
- [8] Federal Communications Commission. 2019. FCC Establishes First Two Innovation Zones. <https://www.fcc.gov/document/fcc-establishes-first-two-innovation-zones>
- [9] Federal Communications Commission. 2019. Use of the 5.850–5.925 GHz Band. <https://docs.fcc.gov/public/attachments/DOC-360940A1.pdf>
- [10] Federal Communications Commission. 2020. 3.5 GHz Band Overview. <https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview>
- [11] Flux Research Group. 2020. POWDER Example Profiles. <https://www.powerwireless.net/example-profiles.php> (Accessible to logged-in POWDER users).
- [12] Mingyue Ji and Rong-Rong Chen. 2018. Fundamental Limits of Wireless Distributed Computing Networks. In *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*. 2600–2608. <https://doi.org/10.1109/INFOCOM.2018.8485811>
- [13] Marcus Karlsson and Erik G. Larsson. 2014. On the Operation of Massive MIMO with and without Transmitter CSI. In *2014 IEEE 15th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. IEEE, 1–5. <https://doi.org/10.1109/SPAWC.2014.6941305>
- [14] Thomas Kidd. 2018. National Radio Quiet and Dynamic Zones. *CHIPS, the Department of the Navy’s Information Technology Magazone* (April–June 2018). <https://www.doncio.navy.mil/CHIPS/ArticleDetails.aspx?ID=10299>
- [15] Thomas L. Marzetta. 2010. Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas. *IEEE Transactions on Wireless Communications* 9, 11 (November 2010), 3590–3600. <https://doi.org/10.1109/TWC.2010.092810.091092>
- [16] Abdelbasset Massouri, Leonardo Cardoso, Benjamin Guillou, Florin Hutz, Guillaume Villemaud, Tanguy Risset, and Jean-Marie Gorce. 2014. CorteXlab: An open FPGAs-based facility for testing SDR & cognitive radio networks in a reproducible environment. In *2014 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 103–104. <https://doi.org/10.1109/INFCOMW.2014.6849176>
- [17] Sriram N. Premnath, Daryl Wasden, Sneha K. Kasera, Neal Patwari, and Behrouz Farhang-Boroujeny. 2013. Beyond OFDM: Best-Effort Dynamic Spectrum Access Using Filterbank Multicarrier. *IEEE/ACM Transactions on Networking* 21, 3 (June 2013), 869–882. <https://doi.org/10.1109/TNET.2012.2213344>
- [18] Dipankar Raychaudhuri, Ivan Seskar, Max Ott, Sachin Ganu, Kishore Ramachandran, Haris Kreimo, Robert Siracusa, Hang Liu, and Manpreet Singh. 2005. Overview of the ORBIT Radio Grid Testbed for Evaluation of Next-Generation Wireless Network Protocols. In *2005 IEEE Wireless Communications and Networking Conference*, Vol. 3. 1664–1669. <https://doi.org/10.1109/WCNC.2005.1424763>
- [19] Dipankar Raychaudhuri, Ivan Seskar, Gil Zussman, Thanasis Korakis, Dan Kilper, Tingjun Chen, Jakub Kolodziejki, Michael Sherman, Zoran Kostic, Xiaoxiong Gu, Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, and Craig Gutierrez. 2020. Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless. In *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (MobiCom)*. <https://doi.org/10.1145/3372224.3380891>
- [20] Michael Rice, Tom Nelson, Joseph Palmer, Christoper Lavin, and Kip Temple. 2017. Space-Time Coding for Aeronautical Telemetry: Part II—Decoder and System Performance. *IEEE Trans. Aerospace Electron. Systems* 53, 4 (August 2017), 1732–1754. <https://doi.org/10.1109/TAES.2017.2671785>
- [21] Clayton Shepard, Rahmon Doost-Mohammady, Ryan E. Guerra, and Lin Zhong. 2017. Demo: ArgosV3: An Efficient Many-Antenna Platform. In *Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking (MobiCom '17)*. ACM, 501–503. <https://doi.org/10.1145/3117811.3119863>
- [22] Clayton Shepard, Hang Yu, Narendra Anand, Erran Li, Thomas Marzetta, Richard Yang, and Lin Zhong. 2012. Argos: Practical Many-Antenna Base Stations. In *Proceedings of the 18th Annual International Conference on Mobile Computing and Networking (MobiCom '12)*. ACM, 53–64. <https://doi.org/10.1145/2348543.2348553>
- [23] Hamed Soroush, Nilanjan Banerjee, Aruna Balasubramanian, Mark D. Corner, Brian Neil Levine, and Brian Lynn. 2009. DOME: A Diverse Outdoor Mobile Testbed. In *Proceedings of the 1st ACM International Workshop on Hot Topics of Planet-Scale Mobility Measurements (HotPlanet)*. <https://doi.org/10.1145/1651428.1651431>
- [24] Boston C Terry, Alex Orange, Neal Patwari, Sneha Kumar Kasera, and Jacobus Van der Merwe. 2020. Spectrum Monitoring and Source Separation in POWDER. In *ACM WiNTECH proceedings*. <https://doi.org/10.1145/3411276.3412192>
- [25] Brian White, Jay Lepreau, Leigh Stoller, Robert Ricci, Shashi Guruprasad, Mac Newbold, Mike Hibler, Chad Barb, and Abhijeet Joglekar. 2002. An Integrated Experimental Environment for Distributed Systems and Networks. In *Proceedings of the 5th Symposium on Operating Systems Design and Implementation (OSDI)*. 255–270.
- [26] Kok-Kiong Yap, Masayoshi Kobayashi, Rob Sherwood, Te-Yuan Huang, Michael Chan, Nikhil Handigol, and Nick McKeown. 2010. OpenRoads: Empowering Research in Mobile Networks. *ACM SIGCOMM Computer Communication Review* 40, 1 (January 2010), 125–126. <https://doi.org/10.1145/1672308.1672331>