

# Lessons from Four Years of PHONELAB Experimentation\*

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## ABSTRACT

Over the last four years we have operated a public smartphone platform testbed called PHONELAB. PHONELAB consists of up to several-hundred participants who run an experimental platform image on their primary smartphone. The experimental platform consists of both instrumentation and experimental changes to platform components, including core Android services and Linux.

This paper describes the design of the testbed, the process of conducting PHONELAB experiments, and some of the research the testbed has supported. We also offer many lessons learned along the way, almost all of which have been learned the hard way—through trial and a lot of error. We expect our experiences will help those contemplating operating large user-facing testbeds, anyone conducting experiments on smartphones, and many mobile systems researchers.

## 1. INTRODUCTION

Smartphones are the most successful mobile devices in computing history. Almost 2 billion of these powerful devices are already deployed worldwide. For many—particularly in developing countries—a smartphone is their only computer and only internet connection. Smartphones provide a rich set of opportunities and challenges for mobile systems researchers as we adapt to a mobile-first world. The global network of distributed smartphones represents the ultimate proving ground for experimental approaches to crowdsourcing, wireless communication, location tracking, energy management, context awareness, security and privacy, user interfaces, and other topics of interest to the mobile systems research community. Smartphones are the ultimate destination for many of our new ideas.

A key challenge when transitioning ideas from local laboratories to the global stage is determining whether they work for large numbers of users. Initial experiments tend to be done by researchers themselves. They are inherently small scale, and use participants that are not representative of typical smartphone users. From an initial small-scale prototype with a handful of sophisticated users, it is a big jump to transition to billions of unsophisticated users. An intermediate

step would help determine whether ideas that initially seem successful are truly ready for widespread deployment.

If a new idea can be evaluated through a smartphone app, experimenters can use smartphone software marketplaces to perform medium-scale studies. Researchers first integrate their new idea into an app—ideally a useful app. Then they deploy it on an app marketplace like the Google Play Store. Recruiting several hundred users to install and use it can be done through a mixture of advertising and participation incentives. Or they may simply count on a combination of human curiosity and the enormous numbers of users they can reach through app marketplaces. Given a large enough audience, even a tiny amount of interest can compound to enough participants to complete a study. Previous experiments have successfully utilized this approach to recruit several hundred participants for a variety of projects [26, 23]. And, when you mix a useful app that meets a common user need with a bit of timely publicity, the results can be explosive. After receiving some good press, the Carat energy management tool was eventually installed by almost 1 million users [26].

But not every new idea can be deployed as an app. Smartphones also run a complex million-line codebase referred to as the smartphone platform, which provides the interface used by apps. On Android the smartphone platform consists of three main components. The Android SDK is built along with the platform into `android.jar` and utilized by all apps. This code runs in the app’s process context and implements many core Android features as well as communication with Android services. Core Android services—such as the `LocationManager`—run as separate processes and communicate with apps to provide information. The Linux kernel performs typical operating system functions such as scheduling and other forms of resource management. Apps rely on—but cannot modify—these platform components.

Because the platform provides functionality needed by many apps, it is also a natural location for mobile systems research and experimentation. Among other responsibilities, the platform estimates location [28, 18, 22, 27], manages energy [19, 26, 34, 13], chooses between networks [29, 12], and attempts to secure the device [24, 5, 6, 20]. All these are areas of ongoing mobile systems research. But that want to evaluate improvements to these core features cannot rely

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on the app store to perform medium-scale experimentation. They require another way to perform their experiments.

For the past four years we have operated a public smartphone platform testbed called PHONELAB. PHONELAB allows researchers to deploy platform modifications to between 100 and 300 participants. Participants use their PHONELAB smartphone as their primary smartphone, and so provide representative usage patterns. Participants are incentivized by a free device, a low-cost service plan, and on-campus technical support. They agree to use experimental software and understand that data will be collected from their device.

Any researcher can distribute experiments on PHONELAB free of charge. We have attempted to make the process as straightforward as possible by providing detailed instructions. But PHONELAB experimentation does require modifying the Android Open Source Project (AOSP) sources—a daunting task for the uninitiated. PHONELAB experiments typically fall into one of two categories. New instrumentation can be added to the platform to generate data about how the smartphone is used. This is a common first step in understanding a problem and beginning to formulate a solution. Instrumentation usually outlives the experiment that introduced it, and our PHONELAB codebase includes an increasing amount of useful logging. When a new feature is ready to be tested, it can also be deployed on PHONELAB—usually along with additional instrumentation required to evaluate it.

Operating PHONELAB has been both fun and challenging. The goal of this paper is to describe the testbed, advertise available data sets, and share what we have learned. Some of our experiences echo those of others that have built and maintained computer systems. But others are specific to the challenge of running a *user-facing* testbed. PHONELAB is more than a set of machines locked in a room [33], tucked into faculty offices [32], or distributed around the world [11]. It is a set of people that rely on their smartphone in the same ways as the rest of us. This creates unique design and operational challenges, particularly given that we allow experimenters to modify low-level platform code. If an experiment crashes a typical testbed, someone may miss a paper deadline. If an experiment crashes PHONELAB, someone may not be able to call 911. We have also encountered unique challenges associated with incentivizing and interacting with participants, providing safe access to data collected from human participants, and dealing with cellular service providers.

## 2. THE PHONELAB TESTBED

In this section, we provide an overview of PHONELAB’s history (§2.1), hardware and software components (§2.2), privacy and safety measures (§2.4) and the transition from app to platform experimentation (§2.5).

### 2.1 History

Figure 1 shows the daily *active* devices during the 4 years of PHONELAB operation. The data is obtained from the

smartphone heartbeat information received by our backend server. The daily active count is a rough estimate but strictly smaller than the total number of participants. Several sudden drops of active count are caused by maintenance or problems with our backend data collection server.

**Year 1 (9/2012–9/2013):** We recruited the first group of 199 participants in September 2012 by offering a free smartphone and a free year of service. Participants were supposed to transition to a paid plan in their second year, but received one year of free service as a recruitment incentive. The first year served as beta-testing of our platform software and data collection framework.

**Year 2 (9/2013–11/2014):** We recruited a second group of 288 participants in September 2013. Although we had hoped that they would continue with the project, most of the Y2 participants were new and most of the Y1 participants left the project. This was caused by poor incentive design, a topic we return to later in Section 6.1.1. PHONELAB opened to the public for app-based experiments in October 2013.

**Year 3 (11/2014–9/2015):** The third year of PHONELAB brought changes to both the incentive model and experimental capabilities. We eliminated the free service plans which were not functioning as an effective incentive for recruiting high quality participants. Instead, we began billing participants at a discounted rate for their cellular service. We began running platform experiments privately early in 2014, and made this capability available to the public in Feb. 2015.

**Year 4+ (9/2015–Present):** Not providing free service lowered the cost of the testbed dramatically and allowed us to continue to run it for another fourth year on three years of initial funding. Given uncertainty about future funding, we stopped recruiting participants in Y4. Attrition began to decrease the size of the testbed.

### 2.2 Hardware and Software

We used Google Nexus devices exclusively through the PHONELAB project. We began with the Nexus S in Y1, and then upgraded to the Galaxy Nexus (Y2), Nexus 5 (Y3–Y4), and Nexus 6 (Y5). We chose the Google Nexus series devices because of its developer support and driver availability.

Once we had a fully-functional Android ROM as a baseline, we made three important modifications to support experimentation. First, we developed a testbed management app called the PHONELAB Conductor. The Conductor is built into the platform and is configured to start on boot. It serves to link each smartphone with our backend server. It sends heartbeats, collects and uploads data, and fetches experiment and platform updates.

Second, we modified the Android `logcat` system to facilitate PHONELAB data collection. The changes include enlarging the in-memory log buffer, increasing the maximum characters that can be logged per line, and improving the timestamp accuracy from millisecond to microseconds. These are very important as we rely heavily on `logcat` and the metadata it attaches when processing logs. We discuss

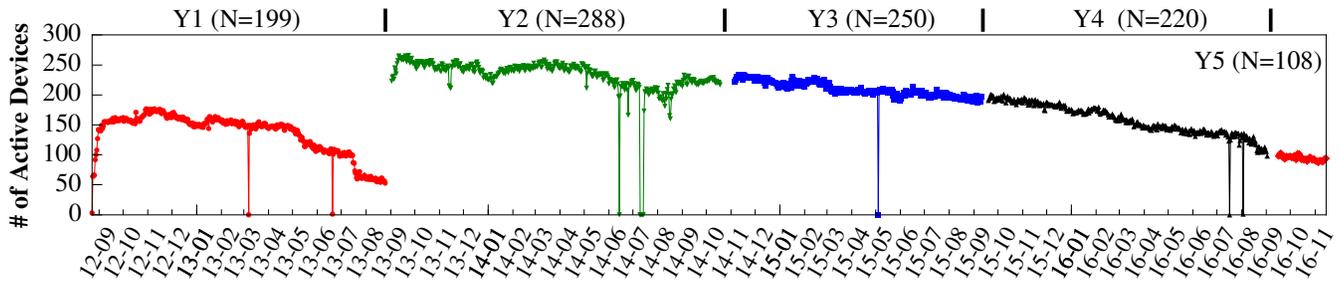


Figure 1: **Daily Active Devices on PHONELAB.** Transition periods between operation years are not shown. There were several sudden drops that were caused by backend server maintenance. The participant counts shown above the figure are when the operation year started.

the detailed data collection mechanism in Section 3.3.

Finally, we added instrumentation to Android to collect information useful to many experiments: location updates, Wifi scan results, battery status changes, etc. All such instrumentation is done passively by piggybacking on places where Android already collects this information. We have been careful to avoid adding any timers or other forms of overhead to our instrumented platform. A full and detailed list of instrumentation can be found on our website<sup>1</sup>. The entire PHONELAB data set is always available to interested researchers, subject to human subjects review. We describe the dataset and data release process in Section 5.

### 2.3 Participants

Almost all PHONELAB participants are faculty, staff and students at our university. When initially providing a free device and service as an incentive in Y1 and Y2, we required a university affiliation in case we needed to recover the device. Once we began billing participants in Y3, that made it possible to recruit from outside the university. If participants stop paying their bills, we simply cancel their service, and so no longer require any additional enforcement mechanisms.

However, we have found it convenient to continue recruiting university participants. It has the effect of making the testbed denser, so most participants spend their working hours on our fairly compact campus. It also allows us to advertise on-campus technical support as an attractive non-monetary incentive. Participants seem to appreciate that they can drop by our lab during office hours for help, rather than having to make a special trip to a cellular store. Despite being all university affiliates, our participants are a diverse group—both in terms of age, gender, and occupation.

### 2.4 Privacy Concerns

Smartphones are personal devices, and can potentially reveal a great deal of sensitive information about their user. When operating our testbed we must take steps to protect the privacy and safety of PHONELAB participants. This is particularly true given that we are now distributing platform updates. Android places limits on what apps can do. But the platform has no such restrictions.

First, all PHONELAB personnel—including faculty, de-

<sup>1</sup>Link omitted for double-blind review.

velopers, and administrators—are required to complete human subjects training. At our university this includes a Good Research Practices (GRP) course and the Social and Behavioral Research Investigators training provided by the CITI program [1]. These programs ensure that the PHONELAB team understands the importance of protecting our participants and best practices for handling PHONELAB data.

Second, we apply standard security techniques to protect data during collection and storage. PHONELAB logs are transmitted to the backend server over HTTPS. The server is located in a secured server room in our department. Access to the server is granted to only a handful of PHONELAB developers who handle data collection.

Finally, all researchers requesting PHONELAB data are required to have their request reviewed for human subjects safety. At US universities, this is done by the Institutional Review Board (IRB). Non-academic institutions and universities outside the US typically have an equivalent body. This is standard practice in any projects that involves human subjects. We are pleased to see IRB review increasing expected by the mobile systems community. We discuss our experiences with the IRB in more detail in Section 6.2.5.

### 2.5 Experiment Model

During Y1 and Y2 of PHONELAB we focused on supporting app-level experiments. Researchers would publish their app on the Google Play Store, and we would notify PHONELAB participants and ask them to install and use it. However, it was challenging to determine whether users were actually participating in these experiments. It was possible to monitor whether they installed an experiment and spent at least some time with it in the foreground. But whether they were using it realistically was difficult to determine. It also became apparent to us that PHONELAB would never provide as many participants as app-level experiments could reach through app marketplaces.

As a result, we began to shift to platform experimentation. This is not only a unique capability that PHONELAB was able to provide, but also made it easier to track participation. For many platform experiments, users participate silently without having to install or use any new software. We do notify users of new platform experiments and provide them with ways to limit data collection on a per-experiment

basis. Starting from Y3, PHONELAB provided only platform experimentation capabilities, and we remain the only public testbed to do so.

### 3. TESTBED OPERATION

In this section, we describe the experiment workflow and operation of PHONELAB. In particular, we focus on the trade-offs we made trying to protect PHONELAB participants from buggy experiments while making PHONELAB operation as transparent to participants as possible.

#### 3.1 Experiment Workflow

PHONELAB experimentation proceeds in three phases: creation, development and deployment.

##### 3.1.1 Creation

Researchers who are interested in PHONELAB first contact us and describe the scope and purpose of the experiment. We review this information based on two criteria: suitability and intrusiveness. Since Y3 PHONELAB has focused on platform-level experimentation. Experiments that can be deployed as apps are encouraged to utilize other approaches such as the Google Play store.

We also evaluate how disruptive the experiment will be to the PHONELAB participants. Experiments that require specific user behaviors or incur large performance or battery penalties will not be deployed. Over the years, we have been impressed, however, with the kinds of experiments that can run without disturbing users. Several times, logging and instrumentation that we were initially worried would cause too high overhead ended up being unnoticeable. As an example, we have instrumented the system call interface to collect file system activity traces. This generates a great deal of output, but has been run successfully without complaint from participants.

Note that IRB approval is not required at this stage. But experimenters are made aware that the IRB letter is necessary for the data collection after deployment. This lowers the barrier for experimenting on PHONELAB, allowing the experimenters to work on the development and IRB application in parallel. The experiment creation stage usually takes just a few days.

##### 3.1.2 Development

After approval, dedicated experiment branch is forked from our AOSP code base where the researchers can stage their modifications. Once experimental changes are ready, a PHONELAB team member checks out the branch and bench tests it on a single device. Assuming that is successful and no glaring problems are immediately apparent, the modified platform is pushed to a small number of PHONELAB developers. Anomalies such as app crashes, performance degradation, and unexpected battery drain are reported at this stage. If problems arise, experimenters are notified and asked to fix them. This step avoids causing problems

for larger numbers of participants that are not developers, and has dramatically reducing the burden of our technical support. The development-testing iteration repeats until all problems detected by PHONELAB developers are fixed.

##### 3.1.3 Deployment

After testing is complete, changes are pushed to testbed participants. Depending on the amount of time requested by the experimenters, this stage can last for weeks, months or years. After the requested period ends, we remove the experimental changes from participant devices. However, if experimenters have added generally-useful instrumentation, we encourage them to merge it into our master development branch. This allows logging for that instrumentation to continue and makes data sets available later to other researchers.

Any researcher can request PHONELAB data sets with IRB approval, and so this process is decoupled from the experimentation workflow. However, most experiments end by researchers requesting a data set containing tags generated by their experiment and other useful information. To assist experimenters during iteration, we can provide small data sets for the purposes of validating their instrumentation without receiving IRB approval. IRB approval is only required once experimenters plan to publish their results.

#### 3.2 OTA Updates

As a smartphone platform testbed, the most important capability is to push platform changes to participant devices. We leverage Android's existing over-the-air (OTA) update mechanism for this purpose. It provides a way to initiate an update to a new platform by applying an update file stored locally. Our job is to generate the update file and reliably transmit the update file to the device. Every time a new platform image is built, incremental OTA update packages are generated against previous platform versions. The PHONELAB Conductor app periodically checks for OTA updates from the backend server, downloads them, and prompts participants to install the update once the download completes. To ensure that updates are eventually applied, the Conductor will automatically apply a pending OTA after midnight once the phone is charging and is not interactively used.

#### 3.3 Data Collection

Android has a built-in `logcat` system that allows apps and various parts of the framework to log debug messages or events. Many useful contextual information are already being logged by the framework, such as screen status, Wifi connection status, battery level, etc. All messages are stored in an in-memory ring buffer. To harvest this information, we harness `logcat` as a sink for our device-end data collection. Experimenters are instructed to log their data using the common `logcat` interface.

We also developed utilities to pipe the Linux kernel logs and the kernel event tracing logs [2] to the `logcat` buffer.

Listing 1: **Various Utilities for Instrumentation.** All log messages are piped to the `logcat` buffer.

```
// Java: use the Log class.
Log.d("MyTag", "Some useful information.");

// C/C++ (user space): use Android ALOG macros.
ALOG(LOG_INFO, "MyTag", "Another useful log.");

// Kernel: use printk and tracing framework
printk(KERN_INFO "Useful kernel logs.");
trace_my_tracepoint(...);
```

This allows us to hook into the existing Linux logging framework. Listing 1 shows examples on how to instrument various parts of the platform.

The PHONELAB Conductor app constantly consumes logs from the buffer and dumps them into log files. These files are then uploaded to our backend server. Similar to OTA updates, the data upload also happens in an opportunistic way when the device is charging.

Once the backend server receives the log files, it performs a series of processing steps to clean them up and add additional information. The resulting log files include a hashed device identifier and the upload time in addition to the original data generated on the device by `logcat`. Logs are sorted into a set of flat files stored on a large RAID array. We currently store one file per day per device containing all generated log messages. To process a data request, we filter the full set of log files by time and by tag to produce the data that is returned to the experimenter.

## 4. EXAMPLE EXPERIMENTS

Over the last two years as a smartphone platform testbed, PHONELAB has accommodated 17 experiments: 8 from PHONELAB developers and 9 from external researchers. In this section, we showcase four experiments<sup>2</sup> that were deployed and evaluated on PHONELAB. We demonstrate how PHONELAB enables researchers to examine real smartphone behavior at scale, and deploy platform changes that cannot be distributed any other way.

### 4.1 Defensive Mobile OS

DEFBOT [5] researchers studied disruptive app behaviors: waking up devices too often, overuse of GPS, and frequent notifications. Disruptive behaviors were detected by tracking the apps's API calls to certain Android platform services, such as `AlarmManager` and `LocationManager`. Defensive actions were enforced by modifying Android to hijack and alter API calls corresponding to disruptive behavior. It is clear that neither the detection nor the defensive actions can be achieved without modifying the Android platform.

DEFBOT was deployed on PHONELAB for over a month from 09/21/2015 to 11/03/2015. The DEFBOT experimenters acknowledged that real deployment on PHONELAB

<sup>2</sup>Information that may reveal author identities, including project names and citations, are concealed for double-blind review.

was helpful to verify that the defending actions did not break the functionality of large numbers of apps used by real users. They also identified the deployment as an opportunity to collaboratively tune defensive policies using feedback from PHONELAB participants and developers.

### 4.2 Lock Screen Analysis

This experiment studied the protection mechanism that users enabled on their smartphone lock screen. The Android framework was instrumented to transparently log the type of each unlock event. Detailed unlocking behaviors, such as time spent on unlocking the screen, number of attempts before a successful unlock, and correlation between PIN length and unlock time, were also logged to study the user interaction with the unlocking mechanism. This information can not be accessed by apps for security reasons, but can be easily logged by modifying the Android platform.

This experiment was deployed on PHONELAB for 8 months from 10/22/2015 to 06/03/2016. Based on the data collected, the experimenters validated the correlation between the user's *securement* sub-scale of Security Behavior Intention Scale (SeBIS) [14] score and the smartphone lock screen usage [6]. Experimenters also identified areas where the lock screen mechanism can be improved to increase usability while still maintaining security [7].

### 4.3 Smartphone Energy Manager

The WATT [8] experiment aimed to separate the energy management mechanism from policy on smartphones. A new Android framework service was developed to add APIs that provide the measurements of per-app energy consumption. It also added new mechanisms to tune app energy consumption via methods such as CPU frequency throttling. These knobs enable user level energy managers to enforce different management policies, rather than relying on policies baked in to the platform itself.

The experimenters also provided several example policies to demonstrate how the WATT framework can be used to write flexible user space energy management policies. Participants were notified the availability of such policies and were encouraged to choose the one they prefer. The WATT experiment was deployed on PHONELAB for over a week from 03/07/2016 to 03/16/2016. An exit survey was also distributed at the end of the study to collect subjective feedback from participants.

### 4.4 Runtime Permission Model

The RTPERM [9] experiment instrumented the Android framework to record resource requests made by application that are protected by installation time permission manifests, such as location, storage, camera, sending SMS, etc. Upon detection of such events, a dialog appears asking the user whether the request would have been declined had they been given a choice. The experiment itself did not block resource access but only recorded the participant's choice. As a result,

it does not affect app functionality.

Based on data collected on PHONELAB participants, the experimenter proposed a runtime permission model where such resource permission shall be granted at runtime when they are requested instead of statically declared in the application’s manifest at installation time. In fact, this is similar to the permission model that was adopted in later Android versions beginning with 6.0. The RTPERM experiment was deployed on PHONELAB for about 4 months from 11/24/2015 to 03/16/2016.

## 5. PHONELAB DATASET

Next, we first briefly describe the available dataset generated by PHONELAB, and the process of data release. Collected data falls into three categories: existing Android logs, instrumentation added by PHONELAB developers, and temporary instrumentation added by experimenters.

### 5.1 Android & Linux Logs

Android’s `logcat` is intended to be used for debugging. During development, app developers can use the `Log` [3] utility to print certain debug information. Upon app crashes, the relevant logs together with stack traces will be upload as part of the crash report. According to the Android development guide, developers are instructed to remove debugging logs in production code. Yet we still found plenty of app-specific log messages in our dataset.

Additionally, logs are naturally generated by many core Android services as well: including the Dalvik and Art Java runtimes, the `SurfaceFlinger` display rendering engine, the core Android UI framework, and other core components. Finally, we also pipe the Linux kernel logs generated by `printk` to the `logcat` buffer. Taken together, this subset of our data represents a unique opportunity to study Android behavior in the wild.

### 5.2 PHONELAB Instrumentations

As part of PHONELAB platform development, we instrumented the Android framework to log various useful information: battery status/level changes, location updates, Wifi scan results, etc. Most of the information can be also obtained from the apps using the Android API. However, we can usually obtain more information inside the framework.

For instance, the `Android TelephonyProvider` service internally records the detailed cellular tower and signal strength information, such as LTE RSRP/RSRQ/CQI. Yet most of this information is not provided to apps. Platform instrumentation allows us to add logging at the place where all available information is still preserved.

### 5.3 Experiment Modifications

Besides augmenting the Android framework with new features, most experiments also added instrumentation to either motivate or validate their experiment. We believe the data can also be potentially useful for other researchers

Category	Tag Count	Line Count
PHONELAB	55	8,674,766,791
Experiments	58	2,471,169,521
Other	12,691	137,714,283,583
Total	12,804	148,860,219,895

Table 1: Overview of PHONELAB Dataset.

Tag	Line #	Description
<code>Kernel-Trace</code>	52.7B	Linux event tracing logs.
<code>SurfaceFlinger</code>	6.1B	Android rendering.
<code>dalvikvm</code>	5.4B	DalvikVM.
<code>MP-Decision</code>	1.8B	CPU hotplug.
<code>art</code>	0.3B	ART VM (after Lollipop).

Table 2: Example Tags Generated by Android Framework and Linux Kernel in PHONELAB dataset.

with similar interests. Examples of such information include SQLite queries, file system access patterns, lock screen behaviors and app energy consumption details.

### 5.4 The Dataset

Over the 4 years of PHONELAB operation, we collected 148 billion log lines totaling 4.6 TB of compressed log files. Each log line contains 6 fields: device ID, timestamp, Linux task ID, log level, tag, and message body. The device ID is a hashed string of the device’s MEID [4], and is guaranteed to be unique to each device and consistent across the dataset. The timestamp field contains the Unix timestamp (with microsecond accuracy) when the log line was generated. The rest of the fields are the same with the `threadtime` format for Android’s `logcat` system. The tag is a string assigned by the developer to identify the purpose or of the log line. Android does not pose any constraints on the format of the message body. To simplify post-processing, we require all logs added by PHONELAB developers or experimenters to use the JSON format for log messages.

Table 1 shows a breakdown of the dataset in each of the three categories. Tags added by PHONELAB developers or experimenters are recognized by an enforced naming convention, which contains the experiment code name and author institution identifier. All tags not recognized by the convention are categorized as “Other”. PHONELAB instrumentation is included in every platform update, while experiment logs are only deployed temporarily. So while certain experiments can generate large volume of logs—file system accesses, SQLite queries—the total number of experiment logs is less than the PHONELAB instrumentation.

Table 2 shows several example tags from the “Other” category. The `Kernel-Tracing` tag includes the log messages from the Linux kernel event tracing [2] framework. Useful informations such as CPU/GPU frequency changes, context switch and scheduling, CPU temperature changes, are logged under this tag. The `SurfaceFlinger` tag is

generated by the Android `SurfaceFlinger` framework, which handles the actual UI and graphics drawing. Information such as frame rate and inter-frame intervals can be obtained to infer UI smoothness and user experience. The `dalvikvm` and the `art` tags are generated from the Dalvik Java VM (prior to Android 5.0 Lollipop) and the new ART VM. Existing `dalvikvm` logging exposed information about garbage collector activity. Finally, the `MP-Decision` tag is generated by the proprietary CPU hotplug feature found on Qualcomm chips. It records the status of cores as they are brought online and offline as needed.

## 5.5 Data Release

We are working on an online catalog of the PHONELAB dataset. Once complete, it will allow researchers to browse the available data and decide the list of tags and time range of interest. An IRB approval is required to submit a data request. Since most of the data does not contain any personal identification information, we expect IRB exemption in most cases. After reviewing the IRB letter, we will collect and provide the requested subset of the data.

## 6. LESSONS LEARNED

We have learned a great deal from building and operating PHONELAB. Below we attempt to distill some of the lessons we have learned along the way. Some of the lessons will not surprise those that have built and maintained large computer systems, particularly user-facing ones. We hope that these lessons are valuable to anyone in the mobile systems community contemplating experimenting with human subjects.

### 6.1 Managing Participants

PHONELAB is nothing without the human participants that choose to participate in the project. And so our first set of lessons concerns how to recruit and manage human participants. This is a challenge not faced by equipment-only testbeds such as EmuLab, PlanetLab and MoteLab. A computer does not decide that it wants to quit the testbed and join some other project. And a computer does not get angry because it came by for help five minutes after office hours ended and the PHONELAB administrator had already left. Given a fixed amount of resources—money or staff time—the goal is to jointly maximize the size and quality of the participant pool. With this goal in mind, we offer the following recommendations.

#### 6.1.1 Get the Incentives Right

**Lesson:** *When you give someone something for free, they are free to treat it like it has no value.*

During the first year of PHONELAB participants were offered a free smartphone and free cellular service—including unlimited text, talk, and data. The original plan was that we would incentivize participants with a free year and then move them to a revenue-neutral paid plan for subsequent years. As a result, a large amount of the \$1M grant from the

NSF was dedicated to paying cellular service fees to Sprint to cover project participants.

As you would expect, it was *very* easy to give out 200 free phones with free service. Everyone loves free stuff. And it was easy on our PHONELAB administrators and staff. There was no billing to do, and because participants were not paying anything their customer service expectations were low.

We had been careful to instruct participants to use the PHONELAB smartphone as their primary device. But as we began examining the data, we realized that many of them were not. When the year ended and we began to retrieve devices, some were still in their original shrink wrap. Other participants were clearly just using the device for data tethering, or to experiment with Nexus smartphone and test out Sprint's service. Overall the free service incentive made it easy to recruit a large number of participants, but hard to recruit high-quality participants.

Despite the warning signs in Y1, we continued the same free service model in Y2—and experienced the same set of problems. Luckily by Y3 we were already moving to a different payment model. We would like to claim that this was done consciously to improve the quality of our participant pool. But in reality it happened because of a miscommunication with Sprint. We had understood that they could provide individual liable plans to participants at the discounted group rate that we had negotiated. This turned out not to be the case. Instead, we had to keep participants on the corporate liable plan and begin handling billing ourselves.

Once we began charging participants a few things changed immediately. First, we had to work harder to recruit participants. That was expected. But second, we began to see a large increase in participants porting their existing number into the project. This turned out to be a very good sign, and something that we should have looked for earlier. It indicated that participants were moving their existing cellular identity on to their PHONELAB smartphone, a clear signal that it was now their primary device.

To examine the effectiveness of the incentive adjustment, we compare the ratio of daily active devices before and after the change. The ratio indicates the percentage of participants that are using their device daily, and probably as their primary device. Figure 2 shows the CDF of daily active ratios for Y1 and Y3. We can see that participants who paid for service (Y3) are more likely to use the device than people who received service for free (Y1). The daily active ratio for Y3 consistently falls in the 80%–90% range.

Getting the incentives right was probably our biggest challenge and getting them wrong our biggest mistake. While it all seems obvious in hindsight, we burned through two years and a large amount of funding before assembling a high-quality participant pool. In retrospect, there were several compounding factors that contributed to this error. First, like most computer scientists, we were overly focused on system building and neglected the human aspects of the project. This myopia may have also effected proposal reviewers and

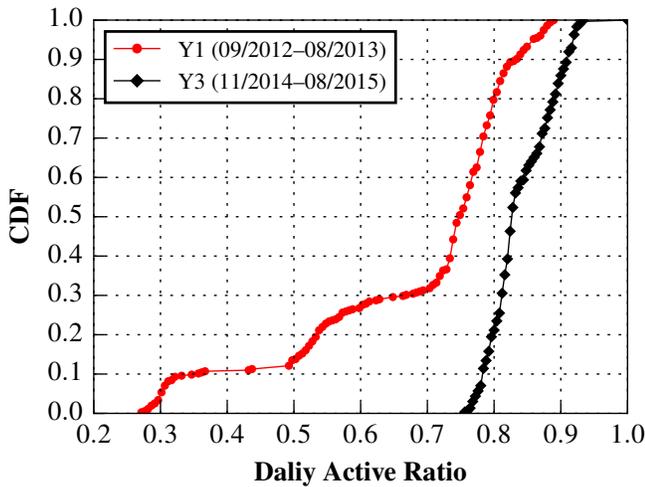


Figure 2: **CDF of Daily Active Ratio for Y1 and Y3.** Days when the backend server was down are not counted. Switching from free (Y1) to paid service (Y3) improves the ratio of active devices.

others that commented on the project at early stages. Despite clear problems with our incentive design, we cannot recall anyone raising concerns about that part of the project.

Second, our proposal was set up to pay for service fees. We went to a lot of trouble to get those allocations approved, and it would have been difficult to reuse them for something else. In today’s funding climate, nobody ever wants to turn away funding. But we probably would have needed to in order to reconfigure the award to remove the service fees.

Finally, we had set an aggressive growth target of reaching 1000 PHONELAB participants in three years. Today that number seems both ludicrous and unnecessary. There is great value in being able to move an experiment out of a small-scale lab setting and on to 100 participants. But at that point, the marginal improvement in moving to 1000 participants is limited. We have never had an idea that we could not evaluate because PHONELAB did not have 1000 participants. Nor has any experimenter ever expressed a need for that scale. But in the early years, faced with a need to grow the project and the funds available to do it, it was easy to stick with the option that made it easy to recruit participants—even if they were low-quality participants.

### 6.1.2 Emphasize Non-Monetary Incentives

**Lesson:** *Monetary incentives are expensive.*

The monthly price that we currently charge participants is not much lower than what they could get on the open market. In fact, most family plans are usually cheaper, and so most of our participants are not in a position to join a family plan. As a result, to incentivize participants to join we have had to construct and emphasize non-monetary incentives.

One that has been simple and effective is highlighting the fact that PHONELAB offers friendly and convenient on-campus technical support. We advertise drop-in office hours where participants can come by and receive help with their

PHONELAB smartphone. Common reasons for visits include broken or lost devices, configuration problems, or performance concerns. This turns an irritation—we have to provide first-level customer service—into a selling point.

Given the compact layout of our university’s campus, our lab is easier for participants to visit than nearby Sprint stores. And the service they receive is both different and better than what they would receive in a store. Our current PHONELAB administrator is more technically savvy and resourceful than your average cellular store employee. Unconstrained by corporate policies, he is free to focus on providing the best service possible to participants.

### 6.1.3 Don’t Be Afraid to Drop Participants

**Lesson:** *When 5% of participants cause 95% of your problems, you can easily eliminate 95% of your problems.*

Paying participants have greatly improved the quality of the PHONELAB testbed. But when you start charging participants, expectations change. Not only do we now have to handle billing and manage cash flow, but we also act as a first point of service for PHONELAB participants.

Not all participants are created equal. Some pay their bills on time, read your emails, come in for help at designated times only when they have a serious problem, and interact well with your staff. Others miss every billing cycle, ignore your emails, drop by your lab at any time with any kind of minor smartphone irritation, and verbally abuse your staff. One participant in particular made it a point to call our administrator at late hours to tell him his phone is having issues and that the administrator was putting his patients at risk as a result of the device not working properly.

After removing the free service incentive, we have had to work hard to recruit participants willing to pay to be a part of a research project. But over time, we have realized that it can be helpful to encourage some to leave the project. Given that we are trying to optimize limited staff resources, retaining participants with above average service expectations is not worth it. Over the past two years, our PHONELAB administrator has been given permission to quietly suggest to some participants that they might be happier with another service provider. And removing the heavy hitters makes it easier to provide acceptable service to remaining participants.

## 6.2 Experimentation

Our second set of lessons concerns how to build a testbed that best supports useful experimentation. Just as PHONELAB is nothing without participants, it is useless without experimenters. The goal here is similar to the goal when building a participant base: maximize the use of the testbed given a fixed set of resources. With this goal in mind, we offer the following recommendations.

### 6.2.1 Eat All of Your Own Dog Food

**Lesson:** *Testbed developers should be testbed experi-*

menters and, if possible, testbed participants.

From the beginning, PHONELAB developers have been both experimenters and participants. As experimenters, they have a direct interest in ensuring that the testbed is usable and effective. PHONELAB developers have contributed much of the current platform instrumentation in support of their own research projects. They have also contributed new experimental features, such as integration with the Linux kernel logging subsystem, again in support of their own work. PHONELAB developers that are also experimenters have stronger incentives to contribute to the project than a developer paid to implement functionality needed by others.

Simultaneously, PHONELAB developers are also participants. The developers form a subset of participants that receive experimental changes first. This is an ideal arrangement. PHONELAB developers are the first group to feel the impact of the changes resulting from a new experiment. And because they are more tech savvy than other participants, they are more sensitive to problems that new experiments may be causing. Developer testing has stopped several experiments from continuing to the full testbed, including extremely obvious regressions (every app starts crashing) and unacceptable performance degradations.

### 6.2.2 Fly Under the Radar When Needed

**Lesson:** *Asking for forgiveness is better than asking for permission. But don't ask, don't tell is best.*

PHONELAB would not be possible without the excellent working relationship we have with Sprint. Cellular providers have a reputation of being difficult to work with. Consider how many research papers describe the performance of “Carrier A” or “a major US cellular carrier”, apparently to avoid jeopardizing a working relationship with an oversensitive company. So many researchers have inquired about how we are able to work so effectively with Sprint.

Luck certainly played a role. We were fortunate to have initial contacts at Sprint that may have been unusually open-minded for the telecom industry. But, more importantly, our initial contacts with Sprint were in sales, not technology or network infrastructure. Our experience has been that the sales side of Sprint is concerned with how many lines we are purchasing and unconcerned with what we are doing with them. We have never concealed what we are doing from Sprint. We have made it clear to them that we are deploying experimental Android platform images to unlocked devices that connect to their network. But we have had the good fortune to be telling the right people. Had we told someone with a deeper understanding of exactly what that meant, it is possible that PHONELAB never would have existed.

### 6.2.3 Go Where You're Needed

**Lesson:** *A good testbed does something that you can't do any other way.*

When PHONELAB was designed and initially funded it

was intended to support both smartphone app and platform experimentation. Because it was easier and safer, work began on app experimentation first, and PHONELAB initially opened with only this capability available.

But it quickly became apparent to us that PHONELAB was neither the only nor the best way to perform app experiments. Deploying an app on existing software marketplaces and encouraging people to install it is a much better approach. Part of this is due to the different distribution model available for apps. But it is also due to the realities of app experiments. PHONELAB could be used to force apps to be installed on participants' smartphones—but we cannot force anyone to *use* the app, or to use it appropriately. That requires a separate set of incentives, or an app that provides obvious benefit to users. Once you solve that problem, the benefit provided by PHONELAB is minimal.

At that point we realized that the platform instrumentation and experimentation capabilities were going to become much more important. We quickly shut down app experimentation entirely and focused all of our efforts on being able to do something that researchers could not do in any other way. Keeping a testbed relevant requires continuously surveying the experimental landscape and identifying a useful niche. To this day, PHONELAB remains the only way to deploy platform changes and collect data from several hundred representative smartphone users.

### 6.2.4 Don't Be Too Afraid

**Lesson:** *Fear is the enemy of user-facing experiments.*

We have always been aware that an errant PHONELAB experiment could cause serious problems for our participants. The ultimate nightmare scenario is a platform update that is so broken that participants have to actually return to the lab for a fix. This would not only represent a nuisance, but a real safety problem for participants that rely on their smartphones in an emergency.

Happily, that has never happened. But we have pushed updates with severe problems. An initial attempt by external researchers to instrument the SQLite database used by Android apps generate an unhandled exception. That caused all Android apps that use SQLite—the vast majority—to crash fairly quickly after launch. Of course, this problem was noticed immediately by our developer testers and a fix followed the initial regression within 24 hours. Luckily, the PHONELAB Conductor that is required to update the platform does not use SQLite and so was not affected by this bug. Had that not been the case, the problem would have been much more severe.

It is important to recognize the potential consequences of poorly-designed experiments when running a human-facing testbed. But it is equally important that that concern not hold back interesting experiments. As we gained experience with platform updates, we overcame initial concerns about systemic failures. We also gained confidence in our ability to catch severe regressions through pre-deployment testing.

## 6.2.5 Offload Human Subjects Review

**Lesson:** *The IRB is an easy human solution to potentially hard or time-consuming technical problems.*

Privacy concerns have always been a part of operating PHONELAB. This is particularly true once we began distributing platform experiments. Android has a permission mechanism that limits app’s access to sensitive information. This is useful when distributing app experiments. But platform code is entirely trusted and runs unconstrained by Android’s permission mechanisms. Distributing platform changes opens the door to all kinds of malicious experiments, which have full access to any and all user data, including things that apps cannot even request access to. For example, it is entirely possible for a platform change to collect and offload a full-resolution video feed harvested from the `SurfaceFlinger` screen buffer. Or implement a key logger to collect user passwords and other sensitive inputs.

We considered multiple ways to try to ensure that PHONELAB experiments were safe for participants. We could have tried to analyze experiments using static or dynamic analysis to determine whether they matched the description provided by the researchers. It is not clear whether this is technically feasible, and would have been unfamiliar terrain for our group which does not study computer security. We also could have inspected them ourselves by examining the source code changes required by the experiment. This would have been time consuming and error prone.

Instead, we fell back on a simpler approach—require that researchers clear their experiment with their Institutional Review Board (IRB) or equivalent. Not all experimenters appreciated this mandate, and we had several cases where interest evaporated once we explained the IRB requirement. And we are definitely aware of frustration and even disdain for human subjects review within the mobile systems community. We have heard the IRB described as a nuisance, and even as something that researchers do as busy work to avoid doing actual research.

But from our perspective the IRB is an ideal solution. Note that we do not believe that most IRBs will adequately review the experiment itself—we could probably do a better job by examining the diffs. The point is not to improve how the experiment is reviewed, the point is to establish a chain of responsibility that avoid us but leads back to the experimenter’s creators. If we review an unsafe experiment incorrectly, then we are partly at fault. If the review process is done by others, we can avoid worrying about culpability.

Overall we believe that the mobile systems research community needs to embrace the IRB process to help protect the work we do with human subjects. It is true that the IRB at many institutions is disturbingly slow and poor at reviewing computer science experiments. But that is not a reason to avoid it—it is an argument for fixing it. And in many cases, PHONELAB experiments have qualified for expedited IRB review due to their limited impact on human subjects.

It is also important to understand when IRB approval is

required and when it is not. Preliminary analysis of data sets that does not reveal information in the form of a publication does not require IRB approval. This allows us to provide experimenters with previews of data sets generated by their experiments or other PHONELAB instrumentation. If the data is useful and they want to proceed to publication, they can initiate the IRB approval process at that point.

## 6.3 Testbed Development and Operation

PHONELAB and other similar testbed are usually run by researchers but are not research projects. As a result, they produce a unique set of development and operational challenges that researchers are not always prepared for. Unlike a research prototype, which only has to work until the paper deadline, testbed software has to work reliably for long periods of time. This is particularly true for testbeds like PHONELAB that have human participants who are generally intolerant of problems and failures. Testbed development is also a great deal of work when measured against certain research incentives—such as publications about the testbed, rather than those that are facilitated by it. And operating human-facing testbeds requires continuous effort and attention. It is not acceptable for the entire testbed to fail for even one day, given that human participants may be affected. Given these requirements, we offer the following recommendations.

### 6.3.1 Do the Minimum

**Lesson:** *Don’t build anything you don’t desperately need.*

PHONELAB was initially extremely overdesigned. There were multiple reasons for this. It is natural to design large and complex “proposal-ware” to try to attract funding. It is also tempting to create new software components to ease the management of a large pool of participants. But regardless of the reasons, we began the project with plans to build many different pieces of software that we ended up not needing. Some of them we wasted time building anyway—others were fortunate enough to slip off of the end of the queue. We estimate that the parts of the PHONELAB software base that are heavily used—over-the-air updates and log data collection—probably represent around 25% of the overall development effort. Not surprisingly, these are the components that are the most immediately obvious and that we would have desperately needed on day 1.

As an example of an unnecessary feature, we initially implemented a heartbeat mechanism. Periodically PHONELAB devices push small pieces of structured data back to our central server. This data is consumed and used to update a variety of different database tables storing metadata about each connected device. However, this information was never frequently used nor completely ignored. It had some limited utility when we were operating our free service plans, since we tried to use it to determine users’ activity levels. But since we have moved to paying participants we have not needed and no longer used this information. Another ex-

ample is the configuration system for the PHONELAB Conductor. We built a fairly complicated system for retrieving configuration parameters from our servers and using them to reconfigure various Conductor components. Most of these parameters, however, have never been changed, and overall the system could have been designed in a much simpler way.

Almost all systems are overdesigned to some degree. But given that PHONELAB was implemented by faculty and students who were also trying to do actual research, the wasted effort is more problematic. Given the chance to start again, we would let our own needs as PHONELAB experimenters drive what needed to be built.

### 6.3.2 Small, Developer-Heavy Teams Are Best

**Lesson:** *Testbed development requires many lines of code and few if any new ideas.*

A typical systems research project that faculty are used to leading involves the exploration of many new ideas through software prototypes. Testbed development is different. It involves the reliable implementation of a few simple ideas—less brainstorming and more testing—less creativity and more coding. As a result, it requires a different kind of team than would be assembled to conduct a research project.

Our experience has been that too many faculty trying to lead a testbed development project tend to slow things down. They tend to come up with ideas faster than available developers can implement them, and have a hard time focusing on the core tasks that need to be done well. In a research project having a bunch of students chasing after a bunch of ideas is fine and even productive. In a testbed project, without new ideas to explore, it's more important to focus on doing a few things well. As funding for PHONELAB dried up, our team shrunk naturally—from five active faculty and three full-time graduate students; to a single faculty member, one part-time graduate developer, and one part-time undergraduate administrator. Far from suffering as staffing was reduced, the testbed actually benefited from a lower decision maker to developer ratio. A lean project team also helps avoid building unnecessary things, as described previously.

## 7. WHITHER SMARTPHONE TESTBEDS?

Public testbeds have a rich history in the systems and networking community. EmuLab, PlanetLab, and MoteLab helped accelerate research in networking, planetary-scale systems, and wireless sensor networks. PHONELAB has successfully supported multiple research experiments and generated a great deal of useful data. We hope that it has had a beneficial effect on the mobile systems community.

But our experience with PHONELAB has made us concerned about the future of this kind of shared infrastructure. Public testbeds require three types of support to succeed. First, they need initial and continued funding. Second, other incentives have to exist encouraging people to build and operate them. Third, they need community buy-in through active experimentation and norms that encourage and require

experimentation at scale to validate new ideas. Today, all three of these sources of support seem increasing uncertain. We discuss each in turn below.

### 7.1 Testbed Funding

At least in the United States, the days where it was easy to get and keep testbeds funded seem behind us. For example, the EmuLab networking testbed received regular infusions of funding from the NSF. Neither PlanetLab nor MoteLab were as successful as EmuLab at obtaining funding, and neither were we. A move toward smaller and more focused awards may make it more difficult to make the significant investments required to build community infrastructure.

User-facing testbeds face their own unique funding challenges. Equipment-based testbeds have large up-front costs and low continuing costs. The testbed funding programs that we are familiar with are set up to reflect this, and often place limits on the amount of operational support that can be included. In contrast, user-facing testbeds can have both large up-front costs and high continuing costs. Continuing to operate PHONELAB requires not only interacting with experimenters, but continuing to handle billing and service requests for PHONELAB participants. Grants for testbeds have also grown shorter, which also challenges user-facing projects. It took us several years to build up a suitable participant base, by which point our funding had almost expired.

We have considered other funding models. We are not in the position to establish a consortium of the kind that successfully funded PlanetLab. Nor do we think that it would be a successful model for smartphone platform experimentation. The small number of companies with the ability to deploy Android platform modifications have the ability to experiment on millions of users. So this is quite a different marketplace than the somewhat larger number of companies with an interest in building planetary-scale systems.

We have also considered charging groups to use PHONELAB. But this runs counter to an established tradition in the research community of offering shared infrastructure free of charge. We also did not want to create additional barriers for groups willing to perform the difficult task of modifying Android.

We hope that funding agencies will consider the challenges of user-facing systems as they plan the next generation of mobile system testbeds. There are exciting efforts underway in the US to build city-scale testbeds that combine wide-area wireless networks with mobile and embedded devices. These testbeds must integrate with smartphones and other user-facing devices. Yes—that does make them much harder and more expensive to operate. But cities of the future will still have people living in them—at least we hope.

### 7.2 Operator Incentives

More significant public funding for earlier testbeds also helped create an incentive for groups to build and operate them. EmuLab grants, for example, were large enough not

only to support testbed operations, but also help support a successful networking research group. But the move to smaller, shorter, and more focused grants removes this incentive for groups to operate testbeds.

Financial incentives for operators are important, but so is community recognition. It is also much cheaper. We hope that the mobile systems community will continue to publish papers describing important tools and infrastructure, even if they do not contain research discoveries. From an efficiency standpoint, building a testbed is probably the worst way to generate a research paper. But if there is no way to publish papers about tools and testbeds, it further drains motivation from their creators and maintainers.

### 7.3 Community Buy-In

Finally, research communities need to support testbeds by using them. This is not as easy as “If you build it, they will come.” We have built PHONELAB, made considerable efforts to publicize the project, and make experimentation as simple as possible. But we have never been satisfied the amount that PHONELAB was used by the mobile system research community.

Why didn’t people use PHONELAB? It is true that modifying Android is hard, and no amount of instructions on our part can mitigate the difficult of experiment-specific changes. But experimenters have to make these changes anyway, regardless of whether they deploy them on PHONELAB or not. We also do require that experimenters receive IRB approval, for reasons explained earlier, and know for a fact that that has turned some away. But at many institutions this is more of a nuisance than a good reason to not do a large-scale experiment. Given that AOSP is more of a code dump than an open source project, there is also not an easy route for successful changes to make their way into actual Android releases. But this does not distinguish research done on PHONELAB from many other kinds of system building where it is the ideas, rather than the artifacts, that may someday have an impact on a product.

We believe that the most important reason is that community has not demanded that researchers perform larger-scale experiments. To a certain degree, as long as researchers can get away with publishing papers based on small-scale studies, they will continue to do so. Running experiments on testbeds like PHONELAB not only takes time and energy, but also may challenge conclusions drawn from small-scale studies. We regularly read papers that present results from small-scale studies that could have been run on PHONELAB. Stronger community norms are needed to encourage researchers to make use of available testbed facilities when appropriate.

## 8. RELATED WORK

The NETSENSE [30] project has been using smartphones to study the social interaction between college students. Free Nexus S smartphones were distributed to 200 univer-

sity freshmen for two years. The smartphones ran modified CyanogenMod and instrumentation was added to log the communication events—such as phone calls, SMS, Facebook posts and Bluetooth proximity. Unlike PHONELAB, NetSense focuses on behavioral rather than systems experiments. The testbed is not open, nor is there a way to distribute platform modifications. At this point NetSense has moved to running as an app and utilizing a “bring your own device” model, rendering it complicated or impossible to perform platform experiments.

LiveLabs [21, 10, 16] is a human behavioral experiment testbed utilizing smartphones. They do not hand out smartphones nor control the platform, but instead deploy experiment software on participants’ own devices. Because of this, LiveLabs is able to scale up to several thousands of participants spanning three venues, including university campus, a resort island and a large convention center. LiveLabs has different aims than PHONELAB. Its goal is to enable more pervasive computing experiments, rather than work on smartphone systems.

Finally, SmartLab [17] is a smartphone testbed consisting of 40 Android smartphones. The smartphones are connected to a hub via USB and user interactions are simulated through a web-based remote screen terminal. The devices are neither mobile nor used by real users. PHONELAB provides a level of realism that SmartLab lacks.

There are also various attempts to deploy experiments as apps on software marketplaces. MobiPerf [15] is an Android app that utilizes the Mobilyzer [25] library to perform network measurements, such as bandwidth and latency testing. The app was deployed on the Google Play store and has over 10K installations so far. Device Analyzer [31] is a Android data collection tool that collects various information at background, such as phone charging status, phone calls, Bluetooth proximity, and so on. Different with MobiPerf, Device Analyzer does not provide value as the app and relies on voluntary participation. Compared to app-based measurement tools, PHONELAB has access to unfiltered more detailed information by instrumenting the smartphone platform.

## 9. CONCLUSION

To conclude, we have described the PHONELAB smartphone platform testbed. We have provided a description of the testbed and an overview of how the testbed works. We have described example PHONELAB experiments and provided an overview of available PHONELAB datasets. We have attempted to distill some of the lessons that we have learned while building and operating PHONELAB, and discussed some of the implications of our experiences for the next generation of mobile systems testbeds.

Unfortunately, funding for PHONELAB will run out at the end of next year, and so experimentation will cease in mid-February 2017. We will continue to provide access to our data sets after that point, and offer up our software for anyone with similar data collection needs. Although

PHONELAB is ending in its current form, we are committed to maintaining experimental access to this important codebase. We plan to approach the CyanogenMod community to see if they are willing to participate in a future incarnation of PHONELAB. Experiments that only include modders will lack the realism that our current participant base provides. But this approach may allow us to continue platform experiments at an even lower overhead.

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