RESEARCH STATEMENT

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I lead blue systems research group and direct the PHONELAB smartphone platform testbed. My group currently consists of six Ph.D. candidates and a varying number of Masters and undergraduate students. I graduated one Ph.D. student, Anand Nandugudi, in 2015. I anticipate that Anudipa Maiti will graduate in 2017 and Jinghao Shi and Guru Prasad in 2018. My group is currently supported by six research grants, including five NSF awards totaling $2,594,461 and a $38,656 Google Research Award. I am PI on five of these awards totaling $2,494,461. My $557,481 CAREER award is currently in the process of being funded.

Together, blue designs, builds, and evaluates novel computer systems. We are currently focused on smartphones. Considered alone, smartphones represent the most capable and successful pervasive computing technology ever deployed. Considered in aggregate, the worldwide smartphone deployment comprises the largest distributed system ever built. We attempt to unlock the full potential of these transformative devices. Our work spans multiple areas of computer systems, including hardware-software co-design, OS energy management, wireless networking, database optimization, crowdsourcing, language design, protocol verification, quality of experience, and ubiquitous computing. We have published 10 papers in selective peer-reviewed conferences and 5 papers in selective peer-reviewed workshops. As of August 1st, 2016, my h-index is 14 and my papers have been cited 5214 times.

My group's research and operation of the PHONELAB testbed have significantly increased the visibility of mobile systems research at UB. We published UB's first paper at UbiComp, the top conference in ubiquitous computing. We also published UB's first papers at HotOS and HotNets, top workshops in operating systems and networking, respectively. I am the first UB faculty member invited to join the technical program committee of multiple top conferences and workshops in mobile systems (MobiSys, MobiCASE, HotMobile) and sensor networking (SenSys, IPSN, and EWSN). Below I discuss some of my group's current and future research efforts. I begin by discussing the PHONELAB smartphone platform testbed which supports most of our ongoing research projects.

1 — PHONELAB: A PUBLIC SMARTPHONE PLATFORM TESTBED

Funding: CI-ADDO-NEW, NSF, $1.3M, 6/2012–12/2016; CI-SUSTAIN, NSF, $75K, 9/2016–9/2017
Publications: NetMob'13; SENSEMINE'13; GetMobile'16; has supported many others

All smartphone apps rely on functionality provided by the underlying smartphone platform. It is responsible for conserving energy, determining which network connection to use, accurately determining the devices location, and other critical tasks. How well it performs these functions affects all installed apps. And yet, while the Android Open Source Project (AOSP) makes it possible for researchers to modify the Android smartphone platform, it is difficult to deploy and evaluate changes on more than several devices.

PHONELAB addresses this experimental gap by allowing researchers to modify the smartphone platform installed on several hundred users smartphones. PHONELAB consists of 125 participants who carry smartphones running a custom PHONELAB Android platform image maintained by the mobile systems and networking community. It contains a mixture of instrumentation and novel features that are being evaluated. Once projects are reviewed for human subjects safety, researchers can download PHONELAB datasets.

Currently the testbed is running multiple experiments from researchers across the country, while also supporting my group's new projects on smartphone thermal management and quality of experience. Both the rate at which new experiments are being distributed and citations of the PHONELAB paper indicate that it has established itself as an important resource for the mobile systems community. Almost all PHONELAB experiments can be performed in no other way, since no similar public facility exists.

Although PHONELAB consumed a great deal of my time and energy as I began my position at UB, I believe that the investment has paid off. Not only is the testbed a highly-visible project within my research community, it has also provided my group a unique tool for pursing our own research. Almost all of our projects are either based on PHONELAB data or evaluated on PHONELAB. PHONELAB is funded through 2016–2017 and I plan to continue to procure funding for and operate the testbed.

2 — IMPROVING SMARTPHONE ENERGY MANAGEMENT

Funding: CSR Small, NSF, $500K, 9/2014–9/2017; CSR Medium, NSF, $561K, 9/2014–9/2017
Publications: HotOS'11, HotMobile'14, IIWSC'14, HotMobile'15, MobiCASE'15, ICCD'16

Smartphone energy consumption is frequently reported by users as their top complaint with today's smartphones and as a worsening problem. My group is addressing this problem in two ways. First, at the hardware-software boundary, smartphones are integrating multiple hardware components presenting significant performance-efficiency tradeoffs. Processors and memory can scale voltage and frequency to become more efficient as they slow down. Multiple radios can be used interchangeably and tune themselves to trade off efficiency for latency or throughput. Multiple performance-efficiency introduce a new challenge. Energy-efficient systems must continuously select the right balance of component settings to maintain performance while conserving energy. We refer to this ability as *power agility*. We are collaborating with computer architects Mark Hempstead (Tufts) and Rizwana Begum (Drexel). Guru Prasad is the lead student at UB. After presenting design principles for power-agile systems, we have explored the relationship between component settings and energy efficiency. Recently we have presented new algorithms for tuning multi-DVFS systems under energy, rather than performance, constraints. Guru Prasad has also begun investigating the relationship between device temperature and energy consumption.

Second, within the Android platform we are exploring new approaches to flexible personalized energy management. Analysis of PHONELAB data shows variation in user charging, lifetime expectations, energy usage between apps, energy usage between the same app across multiple users, and in the energy consumption of one app used by a single user. Yet despite this variation, most approaches to managing smartphone energy consumption take a "one size fits all approach". To respond to this variation we are developing Jouler, a policy-driven energy management framework for Android smartphones. Jouler does not attempt to impose a single energy management policy, but rather embodies the design principle of separating policy and mechanism. Jouler allows new energy management apps to implement their own policies that can respond to differences between users and devices. Switching between policies is as easy as installing a new smartphone app. Jouler also includes new Android interfaces to allow the energy manager to control apps and to allow apps to cooperate with the energy manager. Anudipa Maiti leads the project at UB and has built and evaluated a Jouler prototype. She is also investigating new ways to measure the value that apps deliver so that energy usage can be put into context.

3 — HARNESSING SMARTPHONE VISIBILITY THROUGH POCKETSOURCING

Publications: UbiComp'14, HotNets'14, MobiCASE'14, HotMobile'15, HotWireless'15, INFOCOM'16

Smartphones are always-on and go everywhere we do. We have explored how smartphones can leverage this visibility through an approach we call *pocketsourcing*. Unlike crowdsourcing, pocketsourcing *must not* require user interaction and leverage only what smartphones can learn from inside a pocket.

As an example, we used pocketsourcing to find parking spots on campus. Existing solutions to this problem include onerous requirements such as additional infrastructure, on-vehicle equipment, vehicular networking, or manual user input. In contrast, our solution, PocketParker, requires no additional infrastructure, vehicle modifications, or user input—only installation by a small percentage of users parking in a given lot. PocketParker runs in the background and uses the accelerometer to detect parking lot arrivals and departures, which are forwarded to a central server. There they are incorporated into per-lot availability models allowing PocketParker to accurately order lots by the availability. We built, deployed, and evaluated PocketParker at UB and found it to be lightweight and accurate. Anand Nandugudi led the project. In a separate pocketsourcing project, Anand also showed that smartphones could be used to create distributed storage clouds, joining available storage on multiple devices into a single reliable volume.

Smartphones also provide an ideal vantage point for monitoring wireless networks. Android smartphones are constantly probing the wireless environment. However, today this data is used locally and then discarded. Working with Aaron Striegel (Notre Dame), Jinghao Shi has shown that this data can be useful for improving enterprise network configuration. It can also enable new wireless networking usage models, such as pair-wise reciprocal sharing of access points between neighboring apartments. A group of undergraduates led by Grant Wrazen and Vighnesh Iyer is continuing the project by building a library and several useful apps aimed at personal wireless network monitoring and configuration.

4 — CURRENT AND FUTURE RESEARCH DIRECTIONS

Below I present several new projects that are at a more preliminary stage. I expect that they will form the core of my reseach agenda for the next few years.

4.1 — Harnessing Implementation Flexibility

Funding: Faculty Research Award, Google, $38K; **Publications:** HotMobile'15

Adaptation has long been considered a key to effective mobile systems. On today's smartphones, adaptation is more important and challenging than ever. Smartphones face traditional adaptation challenges: rapidly changing conditions caused by mobility, and resource constraints inherent to battery-powered devices. But for an app to perform well on billions of smartphones, it must also adapt to the significant differences between devices, users, and environments. Realizing the next generation of transformative mobile apps requires novel techniques to make adaptation easier and more effective. I am exploring a new approach to this problem that uses machine learning to harness exposed implementation flexibility. Support from Google is allowing us to build a first version of the system that can adapt decisions to static device and environmental attributes. My CAREER award explores this idea in much greater depth, including automated pre-deployment testing, autogenerated temporal adaptation policies, development and language support for exposing flexibility, and support for other programming environments.

4.2 — Optimizing Smartphone Databases

Funding: CRI-P, NSF, $100K, 8/2016–2/2018; **Publications:** TPCTC'15

Smartphone apps make heavy use of structured storage—embedded SQLite databases on Android. However, databases have been optimized for very different workloads than apps produce. Together with Oliver Kennedy and Lukasz Ziarek we are working on ways to automate the process of creating app-specific smartphone database benchmarks. Undergraduates Grant Wrazen and Lakshmi Ethiraj are currently working on initial processing of database traces collected on PHONELAB.

4.3 — Validating Wireless Protocols

Publications: RV'16

Runtime validation of wireless protocol implementations cannot always employ direct instrumentation of the tested device. It may not implement the required instrumentation, or instrumentation may alter its behavior. Wireless sniffers eliminate the need for instrumentation but introduce new validation challenges. Losses caused by wireless propagation mean that sniffers cannot perfectly reconstruct the device's packet trace. As a result, accurate validation requires distinguishing between specification deviations that represent errors from those caused by sniffer uncertainty. In collaboration with Ranveer Chandra and Shuvendu Lahiri at Microsoft Research we are exploring ways to exploit sniffers to validate wireless protocols. Jinghao Shi leads the project at UB. Beginning with a state machine representing correct protocol behavior, we produce an augmented state machine with extra transitions reflecting sniffer uncertainty. Validating a trace then reduces to determining whether it is accepted by the augmented state machine. Because the sniffer introduces probabilistic transitions, the search space expands exponentially and search can be shown to be NP-complete. However, in practice simple heuristics can limit the search space and keep it tractable. Our approach has successfully detected both synthetic and previously unknown implementation errors.

4.4 — Improving Smartphone Quality of Experience

Resource management is an operating system responsibility. However, frequently resources are managed without an understanding of their connection to what smartphone user care about: *quality of experience* (QoE). For example, when prioritizing multiple network streams the stack is unaware of which is providing information that the user is actively waiting for. Together with Z. Morley Mao (Michigan) we are exploring ways to quantify and improve smartphone QoE. Scott Haseley leads the project at UB. We are currently exploring how to detect active waiting at multiple levels of the graphic stack. Our detector will allow us to quantify waiting, explore its root causes, and help the system address the bottleneck in real time. Future work will formulate and utilize new metrics to quantify smartphone QoE.