

Research STATEMENT

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Introduction: Research Philosophy

My research philosophy revolves around the belief that successful systems research has to demonstrate two things: 1) a novel and interesting approach to an important research problem, and 2) usability. I strongly believe that for a system to be successful, it has to be usable by the target audience. On the other hand, a highly usable system that doesn't advance the state of the art in any way is not particularly interesting from a research perspective either.

My research style is strongly systems-oriented with a large emphasis on hands-on system implementation. A real implementation is crucial, in my opinion, for testing complicated distributed systems as the complexity inherent in these systems is incredibly hard to capture by simulation studies alone. A real implementation is also vital in validating the usability of the system. In addition, the software artifacts from such implementations are important contributions that drive future research and even product development in the area. I am also a strong proponent of collaborative research. Modern systems are so complicated that it is impossible for one person to have all the answers to every problem encountered. As such, I tend to work with at least 2 to 4 other people, each with slightly different skills and backgrounds, to tackle a large systems problem. This multi-disciplinary approach is very apparent in all my research undertakings.

Finally, I strongly believe that it is better to take more time and do something well and then submit it to the best venue possible instead of submitting piece-meal as research is finished. As such, even though my total number of publications may not be that high, almost every publication is published in the top venue (ICSE, FSE, MobiSys, Infocomm, etc.) for that research area. I describe some of these undertakings along with avenues of future research in the next few sections.

Overview of Key Research Milestones and Awards

- 1) Published numerous top-tier research papers in venues such as MobiSys, ICSE, FSE, and Infocomm
- 2) Co-Director of the LiveLabs Urban Lifestyle Innovation Platform. This is a large effort involving multiple external partners and I have been involved from the conceptual stage all the way to the current research and operational aspects.
- 3) Obtained over SGD \$12 million in government research funding in the last 10 years. The funding is as follows:
 - a. MOE ACRF Tier 2 entitled "Power and Network-Aware Software Infrastructure for Multiplayer Mobile Games". This project was worth ~ SGD \$1 Million and I was the principal investigator. The other two co-PIs were from NUS. This project was from December 2008 until May 2012.
 - b. MOE ACRF Tier-2 Grant entitled "Energy-Efficient Stream Analytics on Smartphones for Realtime Contextual Insight". This project is worth ~ SGD \$1 Million and I am the co-principle investigator (Archan is the main PI). The project duration is from January 2012 until January 2015.

- c. The LiveLabs Urban Lifestyle Innovation Platform. We obtained SGD \$10 million from Singapore's National Research Foundation (through the Interactive Digital Media Office of the Media Development Authority) for this research initiative. In addition, this tested is expected to receive matching amounts of funding from our industry partners. I am a co-director of this platform and was instrumental in its conceptualization, funding drive, and current operations. The platform is officially funded from April 2012 until March 2017.
- 4) 2 ACM SIGSOFT Distinguished Paper awards for our work in empirical software engineering.
- 5) High visibility in the ACM SIGMOBILE community with invitations to serve as program chair and the steering committee of HotMobile (the top workshop) and to serve on the program committee of MobiSys (the top conference) for the last five years. Was the co-general chair of MobiSys 2016 and a general chair of UbiComp 2018. I am also appointed as the ACM SIGMOBILE Director for Student Engagement. Finally, I was a program co-chair of MobiSys 2019.
- 6) Numerous systems (such as mFerio, myDeal, the LCD and OLED power management systems, GameOn, and our indoor location system) that have been demoed to various companies and researchers as well as one system (the taxi trip prediction system) that has been deployed into a production data center.
- 7) Appointed as an ACM Distinguished Member in Nov 2018.

Primary Research Theme – Mobility

My research revolves around the central theme of mobility. However, I take a holistic view of the theme and look at the problem of mobility from multiple perspectives and in different scenarios. In particular, my research can be characterized into three broad areas: applications, infrastructure, and organizations and processes.

- **Applications** – In this space, I focus on new and novel mobile applications that either extends an existing domain in interesting ways or which enable whole new usage paradigms.
- **Infrastructure** – In this space, I build, develop, and test infrastructure support that either makes it easier to add new applications to a mobile device, makes specific types of mobile applications run more effectively in a mobile context, or allows efficient and effective testing of mobile solutions.
- **Organizations & Processes** – In this last space, I look at the issues involved when organizational processes, in an IT setting, become mobile. In particular, I analyze the issues involved in distributed software development and I am planning to look at the issues involved in migrating enterprise systems from one platform to another.

The timeline below summarizes my various research initiatives and places them into the three areas described above.

Topic	Start	End	Description	Collaborators	Output
Applications Research					
Peer-to-peer easy to user secure mobile payments	2006	2008	We built the <i>mFerio</i> system to allow users to exchange currency, using NFC, by just tapping their phones. The key innovation here was to do it without infrastructure support and in a highly usable fashion	Narayan Ramasubbu (University of Pittsburgh) Jason Hong and Nicolas Christin (CMU)	mFerio was prototyped on Nokia 6131 NFC phones and tested with 75 participants. Research results have been reported in IEEE Computer article and in a full MobiSys research paper. It has been demoed to Tagit, NETS, EZ-

					Link, MAS, and IDA.
myDeal	2008		This applications automatically identifies the best deals for a particular user		myDeal won a SMU Innovation award and could be a viable startup.
User-Centric Mobile Authentication	2008		We created <i>HuMan</i> , a system that generates questions based on past user interactions on their cell phones. The hypothesis is that these questions will allow the user to login without needing to memorize any passwords while still preventing adversarial attacks.	David Lo and Debin Gao (SMU)	We tested HuMan on Nokia and Android smartphones (with 80 participants in total). Our results have been reported in a UbiComp publication.
GameOn	2015		GameOn was designed to offer p2p gaming for commuters on the same bus or train. This has a lot of potential in crowded Asia.	Nairan Zhang (Wisconsin) and Youngki Lee (SMU)	We have a full research paper in MobiSys, a working system demo, and a Youtube demo video.

Infrastructure Research

Cyber Foraging	2000	2006	This was my thesis work which I continued at SMU for a while. I created a methodology and run-time infrastructure for porting large computationally-intensive applications to resource-constrained mobile devices. Note: I have not continued this research after leaving CMU	Mahadev Satyanarayana and James Herbsleb (CMU) Darren Gergle (NorthWestern)	I created a full system, called <i>Chroma</i> , for porting large applications to a mobile device. Chroma has been described in two top-tier MobiSys publications
Massively Multiplayer Mobile Games	2008	2011	This project aims to develop mechanisms to improve the energy usage of mobile phones while they are playing games	A. L Ananda and Chan Mun Choon (NUS) Samarjit Chakraborty (T.U. Munich)	Awarded ~\$1,000,000 MOE Tier 2 Research Grant. I am the project PI Published a series of research papers (in MobiSys, Infocomm, and other venues) showing how to save power for the display and network components.
Improving the operations of a large Taxi fleet	2008		In this project, we are working with a large local taxi operator to analyze and improve their fleet operations. The operator is providing us with their GPS-enabled taxi logs (~ 2.6 billion data points for 6 months of data).	Jason Woodard, Cheng Shih-Fen, Kim Youngsoo, Jiang Lingxiao, and David Lo (SMU)	We have built and deployed a system for identifying the fare and duration of any taxi trip a-priori. This work was described in a MobiSys paper. We are currently building a system to detect passenger demand with any inputs from the passengers themselves.
LiveLabs	2010		The goal of LiveLabs is to build an in-situ testbed (deployed at a university, a public mall, a resort island, and an airport) that will allow the testing of mobile applications, incentives, and interventions on real phones owned by	Archan Misra (SMU) Also working with Victor Bahl and	We have obtained SGD \$10 million in funding from the Singapore government. We have agreements with the airport, mall, and island owners to deploy LiveLabs at

			real people in real time in real environments	Sharad Agarwal (MSR)	their venues. We have 15 full time staff and students building the required LiveLabs software systems. We officially launched LiveLabs in Nov 2011 (event was graced by Singapore's Deputy Prime Minister) and we had a soft launch of the software at SMU in Oct 2011.
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Organizations & Processes Research

Distributed Software Development	2006		In this project, we analyze the issues involved with distributed software development. In particular, we analyzed the efficiency of Indian out-sourcing companies and highlighted inefficiencies in their processes along with remedies for those inefficiencies	Narayan Ramasubbu (University of Pittsburgh)	We have done really well with this research theme, producing three top-ranked conference publications (FSE and ICSE) with two papers winning ACM SIGSOFT Distinguished Paper Awards.
Cost Estimation for Distributed Project	2008	2012	In this project, we develop a new cost estimation method for distributed software projects. Our estimation method uses CASE-based reasoning techniques and incorporates the intrinsic nature of distributed software development into its decision framework.	Narayan Ramasubbu (University of Pittsburgh)	Narayan, the project PI, implemented the CASE-based solution at three Indian software companies and showed that the solution is better than the existing industry-standard estimation methods. This work was described in an ICSE paper.

In the rest of this statement, I describe the more interesting projects from each of the three areas described above.

HelpLab: A Multi-discipline, Large-scale, In-situ Approach to Empowering Students

My current area is to fuse together all the mobile systems work, done over the last decade, into an effort to help students in school environments. In particular, the goal is to passively monitor all the students in a school, identify patterns that indicate negative such as stress, depression, social exclusion etc. and then provide group or community interventions to alleviate the issues detected. We can also use these techniques to detect and promote positive behavioural traits as well, such as leadership, creativity, happiness etc. I managed to convince many colleagues in social sciences, across SMU, and at other institutions in Singapore and the US to work with me on this.

I have already started preliminary work with my graduated Ph.D. student, now post-doc, Camellia. We collected data from 120+ students across 3 different 14 week semesters and used the self-reported ground truth values (what the students provide via regular surveys) to evaluate the accuracy of our stress and depression prediction mechanisms. We found that our stress detector provided about 80% accuracy every 6 days while the depression predictor was about 90% accurate every 15 days. These results are amazing as we are collecting only WiFi signal strengths, for the phone carried by each participant, directly from the infrastructure. We have no other sources of information (cell phone data, app data, personal data, etc.) that we can use for the prediction.

The latest iteration of this work was the Singapore Spacer initiative that provided accurate floor level information about the density of buildings on campus for SMU, NUS, and NTU. This used the core WiFi analytics developed as part of HelpLab.

We are planning to launch a larger program at NUS and SMU to understand issues related to sleep and stress and provide corrective actions for affected students.

Key Publications:

1. *Camellia Zakaria, Gizem Yilmaz, Priyanka Mary Mammen, Michael Chee, Prashant J. Shenoy, Rajesh Balan: SleepMore: Sleep Prediction at Scale via Multi-Device WiFi Sensing. IMWUT (2022)*
2. *Amee Trivedi, Camellia Zakaria, Rajesh Balan, Ann Becker, George A. Corey, Prashant J. Shenoy: WiFiTrace: Network-based Contact Tracing for Infectious Diseases Using Passive WiFi Sensing. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 5(1): 37:1-37:26 (2021)*
3. *Camellia Zakaria, Youngki Lee, Rajesh Balan: Detection of Social Identification in Workgroups from a Passively-sensed WiFi Infrastructure. Proc. ACM Hum. Comput. Interact. 5(CSCW1): 71:1-71:19 (2021)*
4. *"iMon: Appearance-based Gaze Tracking System on Mobile Devices", Sinh Huynh, Rajesh Krishna Balan, JeongGil Ko, Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 5(4) (2021)*
5. *"HeartQuake: Accurate Low-Cost Non-Invasive ECG Monitoring Using Bed-Mounted Geophones", Jaeyeon Park, Hyeon Cho, Rajesh Krishna Balan, JeongGil Ko, Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 4(3): 93:1-93:28 (2020)*
6. *"Detection of Social Identification in Workgroups from a Passively-sensed WiFi Infrastructure", Camellia Zakaria, Youngki Lee, Rajesh Balan. PACMHCI (CSCW), 2021*
7. *"StressMon: Scalable Detection of Perceived Stress and Depression Using Passive Sensing of Changes in Work Routines and Group Interactions", Camellia Zakaria, Rajesh Krishna Balan, Youngki Lee. [PACMHCI 3\(CSCW\)](#): 37:1-37:29 (2019)*
8. *"DeepMon: Building Mobile GPU Deep Learning Models for Continuous Vision Applications", Loc Nguyen Huynh, Rajesh Krishna Balan, Youngki Lee, Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services (MobiSys), 2017.*

The LiveLabs Urban Lifestyle Innovation Platform

LiveLabs in a nutshell can be described as follows: We allowed 3rd party researchers and companies an opportunity to test their mobile applications, incentives, and interventions on the real phones of real users in real environments in real-time. Currently, we are scheduled to provide service at the SMU university campus, a large public shopping mall, Singapore's Changi Airport, and Singapore's premier leisure and tourism island (Sentosa). We will allow this functionality by installing a small application on each participant's smartphone (with their permission of course). This application will report the location and current preferences and context of that participant to the LiveLabs servers. LiveLabs will then use this information to match the participant with the appropriate applications, incentives, and interventions. A key requirement for LiveLabs is to preserve the privacy of the participants and we do this by isolating the participants from the testing companies. In particular, LiveLabs acts as the middleman between researchers and companies and the participants – they do not interact directly. If the LiveLabs vision comes through, companies and researcher will get incredibly high-fidelity testing of their mobile solutions while the participants will receive incentives, applications, and interventions only when they want it at a time and location when they can use it. i.e., nothing a participant receives should be treated as spam by that participant. For example, a participant will receive a discount for coffee just when they reach the coffee store instead of receiving it at home many hours earlier.

LiveLabs has ended and it was very successful! It generated a steady stream of research with a large signed up user base. I am now running a startup, called SenziQ Pte. Ltd., to commercialise key LiveLabs technologies -- in particular the indoor location analytics solutions.

On top of founding the startup, I am still publishing work in the broad LiveLabs space with my graduate students.

The key LiveLabs results were:

- 1) A usable indoor location system that can work with commercial Wi-Fi systems (deployed by Cisco and Aruba)
- 2) A dynamic group detector that can detect if people are moving together *with intent*. The group detector is a very powerful approach that allows us to do more social experiments that includes people who are together,.
- 3) A fully working experiment engine that combines all out solutions together with a compelling UI to allow other researchers to run behavioral experiments on our LiveLabs participants. We are finally seeing experiments being run by external researchers. For example, researchers from Arizona State University, Temple University, Carnegie Mellon University, Emory University, ESSEC Singapore, as well as SMU faculty from the business and social science schools have run experiments on LiveLabs.
- 4) A platform where various types of sensor, applications, and analytics research can be performed. For example, we have research in eating detection using smart watches, occupancy sensing using capacitance touch sensing, p2p gaming using Wi-Fi Direct and BlueTooth, investigation of the differences between groups and individuals, and analysis of the similarities and differences between a person's online profile and their physical behavior.
- 5) A solution for offloading deep learning models to a mobile GPU that was published at MobiSys 2017.

Key Publications:

1. "VitaMon: measuring heart rate variability using smartphone front camera", Sinh Huynh, Rajesh Krishna Balan, JeongGil Ko, Youngki Lee, SenSys 2019: 1-14, 2019
2. "CryptoCurrency Mining on Mobile as an Alternative Monetization Approach", Sinh Huynh, Kenny Tsu Wei Choo, Rajesh Krishna Balan, Youngki Lee, HotMobile 2019: 51-56, 2019
3. "EngageMon: Multi-Modal Engagement Sensing for Mobile Games", Sinh Huynh, Seungmin Kim, JeongGil Ko, Rajesh Krishna Balan, Youngki Lee, IMWUT 2(1): 13:1-13:27, 2018
4. "Empath-D: VR-based Empathetic App Design for Accessibility", Wonjung Kim, Kenny Tsu Wei Choo, Youngki Lee, Archan Misra, Rajesh Krishna Balan, Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services (MobiSys), 2018
5. "DeepMon: Building Mobile GPU Deep Learning Models for Continuous Vision Applications", LN Huynh, RK Balan, Y Lee, Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services (MobiSys), 2017.
6. "LiveLabs: Building In-Situ Mobile Sensing & Behavioural Experimentation TestBeds", Kasthuri Jayarajah, Rajesh Krishna Balan, Meera Radhakrishnan, Archan Misra, Youngki Lee, MobiSys, Singapore, June, 2016.
7. "Small Scale Deployment of Seat Occupancy Detectors", Nguyen Huy Hoang Huy, Gihan Hettiarachchi, Youngki Lee, Rajesh Krishna Balan, International on Workshop on Physical Analytics (WPA) (MobiSys Workshop), Singapore, June, 2016.

8. "Jasper: Sensing Gamers' Emotions Using Physiological Sensors", Sinh Huynh, Youngki Lee, Taiwoo Park, Rajesh Krishna Balan, Workshop on Mobile Gaming (MobiGames) (MobiSys Workshop), Singapore, June, 2016.
9. "DeepSense: A GPU-based Deep Convolutional Neural Network Framework on Commodity Mobile Devices", Loc Nguyen Huynh, Rajesh Krishna Balan, Youngki Lee, Workshop on Wearable Systems and Applications (WearSys) (MobiSys Workshop), Singapore, June, 2016
10. "IoT+Small Data: Transforming in-store shopping analytics & services", Meera Radhakrishnan, Sougata Sen, Vigneshwaran Subbaraju, Archan Misra, Rajesh Krishna Balan, WACI Workshop, COMSNETS, Bengaluru, India, January, 2016.
11. "LiveLabs: Initial Reflections on Building a Large-scale Mobile Behavioral Experimentation Testbed", by Archan MISRA, Rajesh Krishna BALAN, 10/2013, 17, 4 , Mobile Computing and Communications Review (MC2R), ACM SIGMOBILE, 47--59, United States Of America
12. "The Challenge of Continuous Mobile Context Sensing", by Rajesh Krishna BALAN, Youngki LEE, Kiat Wee TAN, Archan MISRA, 01/2014, The 6th International Conference on Communication Systems and Networks (COMSNETS), Bangalore, India
13. "LiveLabs: Building An In-Situ Real-Time Mobile Experimentation Testbed", by Rajesh Krishna BALAN, Archan MISRA, Youngki LEE, 02/2014, The Fifteenth Workshop on Mobile Computing Systems and Applications (HotMobile), Santa Barbara, California
14. "Barometric Phone Sensors - More Hype Than Hope!", Kartik Muralidharan, Azeem Javed Khan, Archan Misra, Rajesh Krishna Balan, and Sharad Agarwal, Proceedings of the 15th Workshop on Mobile Computing Systems and Applications (HotMobile), Santa Barbara, California, February 2014
15. "Handling Location Uncertainty in Event Driven Experimentation", Kartik Muralidharan, Rajesh Krishna Balan, Srinivasan Seshan and Narayan Ramasubbu, Proceedings of the 8th International Conference on Distributed Event Based Systems (DEBS), Mumbai, India, May 2014
16. "The Case for Human-Centric Personal Analytics", Youngki Lee and Rajesh Krishna Balan, Proceedings of the 1st Workshop on Physical Analytics, Bretton Woods, New Hampshire, June 2014
17. "GruMon: Fast and Accurate Group Monitoring for Heterogeneous Urban Spaces", Rijurekha Sen, Youngki Lee, Kasthuri Jayarajah, Archan Misra, Rajesh Krishna Balan, Proceedings of 12th ACM Conference on Embedded Networked Sensor Systems (SenSys), Memphis, Tennessee, November 2014.
18. "The case for smartwatch-based diet monitoring", Sougata Sen, Vigneshwaran Subbaraju, Archan Misra, Rajesh Krishna Balan, Youngki Lee, Proceedings of the PerCom Workshop on Sensing Systems and Applications Using Wrist Worn Smart Devices (WristSense), Saint Louis, Missouri, March 2015 (awarded best paper)
19. "Using infrastructure-provided context filters for efficient fine-grained activity sensing ", Vigneshwaran Subbaraju, Sougata Sen, Archan Misra, Satyadip Chakraborti, Rajesh Krishna Balan, Proceedings of the 13th IEEE International Conference on Pervasive Computing and Communications (PerCom), Saint Louis, Missouri, March 2015.
20. "QueueVadis: queuing analytics using smartphones ", Tadashi Okoshi, Yu Lu, Chetna Vig, Youngki Lee, Rajesh Krishna Balan, Archan Misra, Proceedings of the 14th International Conference on Information Processing in Sensor Networks (IPSN), Seattle, Washington, April 2015

21. "GameOn: p2p Gaming On Public Transport", Nairan Zhang, Youngki Lee, Meera Radhakrishnan, Rajesh Krishna Balan, Proceedings of the 13th International Conference on Mobile Systems, Applications, and Services (MobiSys), Florence, Italy, May 2015
22. "Need accurate user behaviour?: pay attention to groups!", Kasthuri Jayarajah, Youngki Lee, Archan Misra, Rajesh Krishna Balan, Proceedings of the ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp), Osaka, Japan, September 2015
23. "Smartphones and BLE Services: Empirical Insights ", Meera Radhakrishnan, Archan Misra, Rajesh Krishna Balan, Youngki Lee, Proceedings of the 12th IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS), Dallas, Texas, October 2015
24. "Real-time Detection Of Seat Occupancy & Hogging", Huy Hoang Nguyen, Nakul Gulati, Youngki Lee, Rajesh Krishna Balan, Proceedings of the SenSys International Workshop on Internet of Things towards Applications (IoT-App), Seoul, South Korea, November 2015.

Reducing the Energy Consumption of Mobile Displays

A key research area has been looking at reducing the power consumption of mobile devices. There have been many previous solutions for reducing the power consumption of the CPU and network components of mobile devices. However, there is not much related work in reducing the power consumption of the mobile display --- which is odd given that the mobile display, when turned on, consumes at least 40-50% of the total power consumption of the device. However, any power conservation technique must not affect the user experience as the user is usually looking at the screen. In this stream of research, we first looked at mechanisms for reducing the power consumption of LCDs. Our solution is quite simple in theory but works brilliantly in practice. In a nutshell, we increase the brightness of the image being displayed and then compensate by reducing the brightness of the LCD backlight. This reduction in the backlight can save tremendous amounts of power. We implemented our solution in a fast-paced games and showed, via a user study with 60 participants, that we could save up to 40% of the display power with no impact on usability. This translates to an extra 4 to 8 hours of phone lifetime for free!

We then moved on to look at OLED displays which are increasingly common on newer smartphones (especially those from Samsung). These displays are harder to save energy with as they don't use a backlight. Our solution is to darken portions of the screen that are "less important" to the user. We implemented our solution in the Android kernel and tested it with 13 popular applications (Facebook, Twitter, WhatsApp, Firefox, Email, etc.) and 2 games and achieved up to a 40% reduction in the display power consumption. A user study with 30 participants showed that, even though our solution was quite noticeable, it was still very usable. The perceived usability increased even more once the participants understood how much power (with the corresponding increased phone lifetimes) they could save. This work was published at UbiComp 2013 and was very well received.

We worked with Microsoft Research Redmond researchers to understand and reduce the power consumption of Virtual Reality (VR) displays. This is a particularly interesting area of research as VR displays are predicted to be introduced to the market in a big way – led by the HTC Vive and Oculus Rift displays. This work with MSR was accepted by IMWUT and appeared at UbiComp 2018.

Currently, we are working with researchers at Ajou to manage the power of Augmented Reality (AR) devices. Our first piece of work was published at MobiSys 2019 and we are continuing with other types of devices.

Key Publications

- 1) "LpGL: Low-power Graphics Library for Mobile AR Headsets", Jaewon Choi, Hyeonjung Park, Jeongyeup Paek, Rajesh Krishna Balan, JeongGil Ko, MobiSys 2019: 155-167. 2019
- 2) "FocusVR: Effective 8 Usable VR Display Power Management", Tan Kiat Wee, Eduardo Cuervo, Rajesh Balan, IMWUT 2(3): 142:1-142:25. 2018
- 3) "Focus: A Usable & Effective Approach to OLED Display Power Management ", Tan Kiat Wee, Tadashi Okoshi, Archan Misra, and Rajesh Krishna Balan, Proceedings of the ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp), Zurich, Switzerland. Was one of 10 Best Paper Nominees , August 2013
- 4) "Adaptive Display Power Management for OLED Displays ", Tan Kiat Wee and Rajesh Krishna Balan, Proceedings of the Workshop on Mobile Gaming (MobiGames), in conjunction with ACM SIGCOMM, Helsinki, Finland, [Best Paper Award Winner], August 2012. Full paper under review at MobiSys 2013
- 5) "Adaptive Display Power Management for Mobile Games ", Bhojan Anand, Karthik Thirugnanam, Jeena Sebastian, Pravein G. Kannan, Akhihebbal L. Ananda, Mun Choon Chan, Rajesh Krishna Balan, Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services (MobiSys), Washington D.C., USA, June 2011

Improving the Efficiency of Singapore's Taxi Networks

I had the opportunity, in 2007, to talk to the senior management of Singapore's largest taxi company. They explained that they were looking for advanced R&D to help them solve some of the problems that they (being a hands-on logistics company) did not have the capability to solve. I readily took up the challenge as a great opportunity to impact a real company. The first solution we developed for them was a system to predict, a-priori, the expected fare and time for any taxi trip. This is particularly complicated in Singapore as there are various time and location based charges that affect the final taxi fare. In addition, congestion is also location and time correlated. Our solution was to build a super-fast system that is able to, in real-time, compute the expected time and fare for any two points in Singapore (accurate to within 100m for both the start and end positions). The system uses machine learning techniques to quickly find similar historical trips. It then uses those historical trips, coupled with aggressive outlier filtering, to compute an expect fare and time for the proposed trip. Our solution runs in real-time and has an average error of SGD \$1 for the fare and 2 minutes for the time. The company was quite excited by these results and we proceeded to install the system in their data center. This work has been put on hold for now.

Key Publications

1. "[Providing Real-Time Feedback for a Large Taxi Fleet](#)", **Rajesh Krishna Balan**, Nguyen Xuan Khoa, Lingxiao Jiang, Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services (MobiSys), Washington D.C., USA, June 2011

Globally Distributed Software Development: Mobile Org. & Processes

Together with Narayan Ramasubbu (now a faculty member at the University of Pittsburgh), we have analyzed the effect of outsourcing software development to other companies. In particular, we looked at the impact on performance outcomes (such as productivity, errors, and profits) of developing software in a distributed fashion (where the client and development company are not co-located). Our research was facilitated by very high fidelity project data collected from various large software development firms (mainly based in India). Our results were very well received by the software engineering community and we have had numerous papers accepted to the top tier software engineering conference venues (ICSE and FSE). In addition, two of our papers have also won the ACM SIGSOFT Distinguished Paper Award. Our key results show that distributing software development can have terrible impact on project productivity unless corrective actions are taken (FSE 2007 paper). We then showed that using the right process was vital for achieving good project performance (ICSE 2009 paper). We then showed that if you want to achieve the highest profits, you need to configure your distributed software teams in ways that

reduced their overall productivity (ICSE 2011 paper). We then developed and deployed (at three different Indian software companies) a new method to perform cost estimation for distributed software projects (ICSE 2012 paper). This new methods resulted in an average per-project savings of 20% across all three deployment sites. Finally, we also looked at how a large company managed both client requests and bug fixes for a large software product line (FSE 2010 paper). This line of work has been put on hold for now.

Key Publications

1. "[*Overcoming the Challenges in Cost Estimation for Distributed Software Projects*](#)", Narayan Ramasubbu and **Rajesh Krishna Balan**, Proceedings of the 34th International Conference on Software Engineering (ICSE), Zurich, Switzerland, June 2012
2. "[*Configuring Global Software Teams: A Multi-Company Analysis of Productivity, Quality, and Profits*](#)", Narayan Ramasubbu, Marcelo Cataldo, **Rajesh Krishna Balan**, and James D. Herbsleb, Proceedings of the 33rd International Conference on Software Engineering (ICSE), Honolulu, Hawaii, **[ACM SIGSOFT Distinguished Paper Award]**, May 2011
3. "[*Evolution of a Bluetooth Test Application Product Line: A Case Study*](#)", Narayan Ramasubbu, **Rajesh Krishna Balan**, Proceedings of the 18th ACM SIGSOFT Symposium on the Foundations of Software Engineering (FSE), Santa Fe, New Mexico, USA, November 2010
4. "[*The Impact of Process Choice in High Maturity Environments: An Empirical Analysis*](#)", Narayan Ramasubbu and **Rajesh Krishna Balan**, Proceedings of the 31st International Conference on Software Engineering (ICSE), Vancouver, Canada, May 2009
5. "[*Globally Distributed Software Development Project Performance: An Empirical Analysis*](#)", Narayan Ramasubbu, **Rajesh Krishna Balan**, Proceedings of the 6th joint meeting of the European Software Engineering Conference and the ACM SIGSOFT Symposium on the Foundations of Software Engineering (FSE), Dubrovnik, Croatia, **[ACM SIGSOFT Distinguished Paper Award]**, September 2007