Pat Pannuto

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Research Interests and Overview

From mainframes to wearables Bell's law captures the march of progress, noting the emergence of a new computing class roughly every decade. My research explores what will be required to keep enabling these next generations of computing, how insights from the emerging centimeter-scale and nascent millimeter-scale computing class can solve problems across all domains, and how our expectations and interactions with technology will shift as we begin to realize the ubiquitous computing vision.

The **MBus** project considers this from an architectural perspective, finding fundamental area and energy constraints in current interconnect technologies and demonstrating that shifting system management into the interconnect can simplify both system and circuit design.

Slocalization, the first FCC-compliant ultra wideband backscatter platform, is motivated by deployment challenges, giving one answer for how we might manage the deployment of millions of miniature sensors. It demonstrates decimeter-accurate sub-microwatt whole-room concurrent localization, creates a novel integration technique to recover signals from far below the noise floor, and introduces the energy versus latency tradeoff for systems design.

Harmonium explores how to efficiently design an active ultra wideband tag, empowering opportunistic high-fidelity tracking, and first introduced the bandstitching technique that allows access to the ultra wideband channel using widely-available narrowband frontends.

SurePoint investigates diversity in the ultra wideband channel, efficient protocols to capture multiple independent samples, and is the first to demonstrate constructive interference with 802.15.4a.

The **Tock** operating system answers questions of management, bringing proper process isolation to embedded systems via new hardware and language features that afford safety. Tock addresses fundamental robustness and adaptability tensions with the introduction of grants, a mechanism for a statically allocated kernel to safely perform dynamic allocations in process memory.

Luxapose shows how the smartphone camera can recover data from visible lights using the rolling shutter effect and realize centimeter-accurate position and single-degree accurate orientation from the projection of these lights on the camera imager.

Opo crafts a novel, highly efficient ultrasonic wakeup frontend that enables a new broadcast ranging primitive, affording infrastructure-free human interaction tracking with high spatio-temporal fidelity.

Education

University of California, Berkeley, Berkeley, CA (2017–present)
Ph.D. Student in Electrical Engineering (degree expected summer 2019)
Advisor: Prabal Dutta

University of Michigan, Ann Arbor, MI (2012–2017)
M.Eng. in Computer Science
Advisor: Prabal Dutta

University of Michigan, Ann Arbor, MI (2007–2012)
B.S.Eng. in Computer Engineering

Awards and Honors

Fellowships

2013 Qualcomm Innovation Fellowship (Honorable Mention), joint with Bradford Campbell, $50,000

2013 National Defense Science & Engineering Graduate Fellowship (NDSEG), $95,000 plus tuition

2013 National Science Foundation Graduate Research Fellowship (NSF GRFP), $90,000 plus tuition

2012 University of Michigan Department of Computer Science First-Year Fellowship

Publication Awards

2018 Best Paper Finalist, The 17th ACM/IEEE International Conference on Information Processing in Sensor Networks

2017 David Wessel Best Demo Award, TerraSwarm Annual Review

2016 IEEE Micro Top Pick in Computer Architecture

2016 Outstanding Poster Award, Twelfth International Nanotechnology Conference on Communication and Cooperation

2015 Potential for Test of Time 2025 Award, The 2nd ACM Workshop on Hot Topics in Wireless

Teaching Honors

2017 University of Michigan Rackham Graduate School Outstanding Graduate Student Instructor

2017 University of Michigan College of Engineering Richard & Eleanor Towner Prize for Outstanding Graduate Student Instructors

2012 Best Undergraduate Instructor, University of Michigan, EECS

Advising and Mentoring

2018 Andreas Biri, (M.S. in progress): Adaptive protocols for interaction tracking

2014 Noah Nuechterlein, (undergraduate independent study): Applied computer vision

Teaching Experience

Primary Instructor, EECS 398: Computing for Computer Scientists (F16, W16)

A new class designed and built from scratch. This class attempts to address the experience gap that exists across the spectrum of incoming Computer Science students. While driven by tools (shells, build systems, debuggers, version control), it explores how and why computer scientists interface with computers differently in their day-to-day activities, how to apply principles learned in courses to everyday activities, and ultimately how to be a more efficient user of computing resources.

This course has been adopted as part of the permanent curriculum at the University of Michigan as EECS 201: Computing Pragmatics, an advised co-requisite for first-year EECS majors.

https://c4cs.github.io

In 2017, I was awarded the Rackham Graduate School Outstanding Graduate Student Instructor and the College of Engineering Richard & Eleanor Towner Prize for Outstanding Graduate Student Instructors for this course.

Graduate Teaching Assistant, EECS 373: Design of Microprocessor Based Systems (F15, W15)

Undergraduate Teaching Assistant, EECS 470: Computer Architecture (W12)

Undergraduate Teaching Assistant, EECS 482: Introduction to Operating Systems (W12, F11, W11, F10)

Undergraduate Teaching Assistant, EECS 373: Design of Microprocessor Based Systems (F11, W11)

Invited Presentations

Invited Talk: MBus: A power-aware interconnect for ultra-low power micro-scale system design, at DARPA Near Zero Power RF and Sensor Operations (N-ZERO) Program Review (2016)

Invited Talk: Ultra Wideband and Indoor Localization, at HotWireless'16

Keynote Address: The Recent Past and Distant Future of [Micro-Scale] Embedded Systems, at NextMote: Next Generation Platforms for the Cyber-Physical Internet, part of the International Conference on Embedded Wireless Systems and Networks (EWSN'16)

PolyPoint and the First Steps Towards Ubiquitous Localization, at the Student Summit on Mobility, Systems, and Networking, Microsoft Research

Guest Speaker: Sensor Systems and the Art of Effectively Deploying Sensor Networks, TechChange TC111: Technology for Monitoring and Evaluation

Invited Talk: Embedded System Design and the Internet of Things, Stanford Internet of Things Industrial Research Program

Invited Talk: Sensing Technologies for Data Collection and Monitoring, State of the Science, Development Impact Lab (DIL) and USAID Higher Education Solutions Network (HESN)

MBus: Enabling the Next Generation of Sensors and Systems, TerraSwarm Annual Meeting

Professional Service

2018 ACM Workshop on Data Acquisition to Analysis (DATA 18) – TPC Member

2014 ACM Workshop on Visible Light Communication Systems – Demo Co-Chair

Recurring reviewer for IEEE Transactions on Circuits and Systems II (TCAS-II) *2013–present*

Recurring reviewer for IEEE Transactions on Mobile Computing (TMC) *2014–present*

Recurring reviewer for USAID Development Innovation Ventures (DIV) *2015–present*

Computer Science Engineering Graduate Student Body President *2013–2015*

Computer Science Engineering Student Faculty Representative *2015–2016*

References

Prabal Dutta
University of California, Berkeley
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Carnegie Mellon University
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Journal Publications

[1] **Pat Pannuto**, Benjamin Kempke, Li-Xuan Chuo, David Blaauw, and Prabal Dutta. "Harmonium: Ultra Wideband Pulse Generation with Bandstitched Recovery for Fast, Accurate, and Robust Indoor Localization". In: *ACM Transactions on Sensor Networks*. TOSN'18 14.2 (June 2018), 11:1–11:29. ISSN: 1550-4859. DOI: 10.1145/3185752. URL: http://doi.acm.org/10.1145/3185752. **Invited Paper.**

[2] Inhee Lee, Ye-Sheng Kuo, **Pat Pannuto**, Gyouho Kim, ZhiYoong Foo, Ben Kempke, Seokhyeon Jeong, Yejoong Kim, Prabal Dutta, David Blaauw, and Yoonmyung Lee. "MBus: A Fully Synthesizable Low-power Portable Interconnect Bus for Millimeter-scale Sensor Systems". In: *Journal of Semiconductor Technology and Science* 16.6 (Dec. 2016), pp. 745–753. DOI: 10.5573/JSTS.2016.16.6.745.

[3] **Pat Pannuto**, Yoonmyung Lee, Ye-Sheng Kuo, ZhiYoong Foo, Benjamin Kempke, Gyouho Kim, Ronald G. Dreslinski, David Blaauw, and Prabal Dutta. "MBus: A System Integration Bus for the Modular Micro-Scale Computing Class". In: vol. 37. Micro Top Picks 3. May 2016. **Top Pick in Computer Architecture.**

[4] Benjamin Kempke, **Pat Pannuto**, and Prabal Dutta. "Harmonia: Wideband Spreading for Accurate Indoor RF Localization". In: *SIGMOBILE Mobile Computing and Communications Review*. MC^{2}R 18.3 (Jan. 2015), pp. 19–25. ISSN: 1559-1662. DOI: 10.1145/2721896.2721901. URL: http://doi.acm.org/10.1145/2721896.2721901. **Invited Paper.**

[5] Yoonmyung Lee, Suyoung Bang, Inhee Lee, Yejoong Kim, Gyouho Kim, Mohammad Hassan Ghaed, **Pat Pannuto**, Prabal Dutta, Dennis Sylvester, and David Blaauw. "A Modular 1 mm^3 Die-Stacked Sensing Platform with Low Power I^{2}C Inter-die Communication and Multi-Modal Energy Harvesting". In: *IEEE Journal of Solid-State Circuits*. Vol. 48. 2013.

Conference Publications

[6] **Pat Pannuto**, Wenpeng Wang, Prabal Dutta, and Bradford Campbell. "A Modular and Adaptive Architecture for Building Applications with Connected Devices". In: *The 1st IEEE International Conference on Industrial Internet*. ICII'18. Bellevue, WA, USA, Oct. 2018. **Invited Paper.**

[7] Noah Klugman, Veronica Jacome, Meghan Clark, Matthew Podolsky, **Pat Pannuto**, Neal Jackson, Aley Soud Nassor, Catherine Wolfram, Duncan Callaway, Jay Taneja, and Prabal Dutta. "Experience: Android Resists Liberation from Its Primary Use Case". In: *The 24th Annual International Conference on Mobile Computing and Networking*. MobiCom'18. New Delhi, India, Oct. 2018.

[8] **Pat Pannuto**, Benjamin Kempke, and Prabal Dutta. "Slocalization: Sub-µW Ultra Wideband Backscatter Localization". In: *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks*. IPSN'18. New York, NY, USA: ACM, Apr. 2018. Acceptance: 22 / 83 (27%). **Best Paper Finalist.**

[9] Joshua Adkins, Bradford Campbell, Branden Ghena, Neal Jackson, **Pat Pannuto**, Samuel Rohrer, and Prabal Dutta. "The Signpost Platform for City-Scale Sensing". In: *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks*. IPSN'18. New York, NY, USA: ACM, Apr. 2018. Acceptance: 22 / 83 (27%).

[10] Amit Levy, Bradford Campbell, Branden Ghena, Daniel B. Giffin, **Pat Pannuto**, Prabal Dutta, and Philip Levis. "Multiprogramming a 64kB Computer Safely and Efficiently". In: *Proceedings of the 26th Symposium on Operating Systems Principles*. SOSP'17. Shanghai, China: ACM, Oct. 2017, pp. 234–251. ISBN: 978-1-4503-5085-3. DOI: 10.1145/3132747.3132786. URL: http://doi.acm.org/10.1145/3132747.3132786.

[11] Benjamin Kempke, **Pat Pannuto**, Bradford Campbell, and Prabal Dutta. "SurePoint: Exploiting Ultra Wideband Flooding and Diversity to Provide Robust, Scalable, High-Fidelity Indoor Localization". In: *Proceedings of the 14th ACM Conference on Embedded Networked Sensor Systems*. SenSys'16. Stanford, CA, USA, Nov. 2016. Acceptance: 21 / 119 (18%).

[12] Benjamin Kempke, **Pat Pannuto**, and Prabal Dutta. "Harmonium: Asymmetric, Bandstitched UWB for Fast, Accurate, and Robust Indoor Localization". In: *Proceedings of the 15th International Conference on Information Processing in Sensor Networks*. IPSN'16. Vienna, Austria, Apr. 2016. Acceptance: 23 / 117 (20%).

[13] **Pat Pannuto**, Yoonmyung Lee, Ye-Sheng Kuo, ZhiYoong Foo, Benjamin Kempke, Gyouho Kim, Ronald G. Dreslinski, David Blaauw, and Prabal Dutta. "MBus: An Ultra-Low Power Interconnect Bus for Next Generation Nanopower Systems". In: *Proceedings of the 42nd International Symposium on Computer Architecture*. ISCA '15. Portland, Oregon, USA: ACM, June 2015. Acceptance: 58 / 305 (19%).

[14] William Huang, Ye-Sheng Kuo, **Pat Pannuto**, and Prabal Dutta. "Opo: A Wearable Sensor for Capturing High-Fidelity Face-to-Face Interactions". In: *Proceedings of the 12th ACM Conference on Embedded Networked Sensor Systems*. SenSys '14. Memphis, Tennessee, USA: ACM, 2014. ISBN: 978-1-4503-3143-2. Acceptance: 21 / 117 (18%).

[15] Ye-Sheng Kuo, **Pat Pannuto**, Gyouho Kim, ZhiYoong Foo, Inhee Lee, Benjamin Kempke, Prabal Dutta, David Blaauw, and Yoonmyung Lee. "MBus: A 17.5 pJ/bit Portable Interconnect Bus for Millimeter-Scale Sensor Systems with 8 nW Standby Power". In: *CICC '14: IEEE Custom Integrated Circuits Conference*. San Jose, California, USA, Sept. 2014. Acceptance: 94 / 266 (35%).

[16] Ye-Sheng Kuo, **Pat Pannuto**, Ko-Jen Hsiao, and Prabal Dutta. "Luxapose: Indoor Positioning with Mobile Phones and Visible Light". In: *The 20th Annual International Conference on Mobile Computing and Networking*. MobiCom '14. Maui, Hawaii, USA, Sept. 2014. Acceptance: 36 / 220 (16%).

[17] David Blaauw, Dennis Sylvester, Prabal Dutta, Yoonmyung Lee, Inhee Lee, Sechang Bang, Yejoong Kim, Gyouho Kim, **Pat Pannuto**, Ye-Sheng Kuo, Dongmin Yoon, Wanyeong Jung, ZhiYoong Foo, Yen-Po Chen, Jeong Seok-Hyeon, and Myungjoon Choi. "IoT Design Space Challenges: Circuits and Systems". In: *Proceedings of the 2014 IEEE Symposium on VLSI Technology (VLSI'14)*. Honolulu, Hawaii, USA, June 2014. **Invited Paper.**

[18] Gyouho Kim, ZhiYoong Foo, **Pat Pannuto**, Ye-Sheng Kuo, Benjamin Kempke, Mohammad Hassan Ghaed, Suyoung Bang, Inhee Lee, Yejoong Kim, Seokhyeon Jeong, Prabal Dutta, Dennis Sylvester, and David Blaauw. "A Millimeter-Scale Wireless Imaging System with Continuous Motion Detection and Energy Harvesting". In: *VLSI Circuits (VLSIC), 2014 Symposium on*. Honolulu, Hawaii, USA, June 2014. Acceptance: 96 / 420 (23%).

[19] Ye-Sheng Kuo, **Pat Pannuto**, Thomas Schmid, and Prabal Dutta. "Reconfiguring the Software Radio to Improve Power, Price, and Portability". In: *Proceedings of the 10th ACM Conference on Embedded Networked Sensor Systems*. SenSys '12. Toronto, Canada: ACM, 2012. Acceptance: 23 / 123 (19%).

Workshop Publications

[20] **Pat Pannuto**, Benjamin Kempke, Bradford Campbell, and Prabal Dutta. "Indoor Ultra Wideband Ranging Samples from the DecaWave DW1000 Including Frequency and Polarization Diversity". In: *Data Acquisition To Analysis*. DATA'18. Nov. 2018. Acceptance: 14 / 15 (93%).

[21] Joshua Adkins, Bradford Campbell, Branden Ghena, Neal Jackson, **Pat Pannuto**, and Prabal Dutta. "Energy Isolation Required for Multi-tenant Energy Harvesting Platforms". In: *Proceedings of the Fifth ACM International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems*. ENSsys'17. Delft, Netherlands: ACM, Nov. 2017, pp. 27–30. ISBN: 978-1-4503-5477-6. DOI: 10.1145/3142992.3142995. URL: http://doi.acm.org/10.1145/3142992.3142995. Acceptance: 6 / 18 (33%).

[22] Amit Levy, Bradford Campbell, Branden Ghena, **Pat Pannuto**, Prabal Dutta, and Philip Levis. "The Case for Writing a Kernel in Rust". In: *Proceedings of the 8th Asia-Pacific Workshop on Systems*. APSys '17. Mumbai, India: ACM, Sept. 2017, 1:1–1:7. ISBN: 978-1-4503-5197-3. DOI: 10.1145/3124680.3124717. URL: http://doi.acm.org/10.1145/3124680.3124717.

[23] Amit Levy, Michael P Andersen, Bradford Campbell, David Culler, Prabal Dutta, Branden Ghena, Philip Levis, and **Pat Pannuto**. "Ownership is Theft: Experiences Building an Embedded OS in Rust". In: *Proceedings of the 8th Workshop on Programming Languages and Operating Systems*. PLOS 2015. Monterey, CA: ACM, Oct. 2015. ISBN: 978-1-4503-3942-1. DOI: 10.1145/2818302.2818306. URL: http://dx.doi.org/10.1145/2818302.2818306. Acceptance: 7 / 16 (44%).

[24] Benjamin Kempke, **Pat Pannuto**, and Prabal Dutta. "PolyPoint: Guiding Indoor Quadrotors with Ultra-Wideband Localization". In: *2015 ACM Workshop on Hot Topics in Wireless*. HotWireless '15. Paris, France, Sept. 2015. **Potential for Test of Time 2025 Award.**

[25] **Pat Pannuto**, Yoonmyung Lee, ZhiYoong Foo, Gyouho Kim, David Blaauw, and Prabal Dutta. "Lessons from Five Years of Making Michigan Micro Motes". In: *6th Workshop of Architectural Research Prototyping*. WARP '15. Portland, Oregon, USA, 2015. Acceptance: 11 / 20 (55%).

[26] Bradford Campbell, **Pat Pannuto**, and Prabal Dutta. "Interfacing the Internet of a Trillion Things". In: *The Second International Workshop on the Swarm at the Edge of the Cloud*. SEC '15. Seattle, Washington, USA, 2015.

[27] Benjamin Kempke, **Pat Pannuto**, and Prabal Dutta. "Harmonia: Wideband Spreading for Accurate Indoor RF Localization". In: *2014 ACM Workshop on Hot Topics in Wireless*. HotWireless '14. Maui, Hawaii, USA, Sept. 2014.

[28] Ye-Sheng Kuo, **Pat Pannuto**, and Prabal Dutta. "System Architecture Directions for a Software-Defined Lighting Infrastructure". In: *1st ACM Workshop on Visible Light Communication Systems*. VLCS '14. Maui, Hawaii, USA, Sept. 2014.

[29] Noah Klugman, Javier Rosa, **Pat Pannuto**, Matthew Podolsky, William Huang, and Prabal Dutta. "Grid Watch: Mapping Blackouts with Smart Phones". In: *Proceedings of the 15th Workshop on Mobile Computing Systems and Applications*. HotMobile '14. Santa Barbara, California: ACM, Feb. 2014.

[30] **Pat Pannuto** and Prabal Dutta. "Exploring Powerline Networking for the Smart Building". In: *Extending the Internet to Low power and Lossy Networks*. IP+SN '11. Chicago, Illinois, USA, Apr. 2011.

Posters and Demos

[31] Joshua Adkins, Bradford Campbell, Branden Ghena, Neal Jackson, **Pat Pannuto**, Samuel Rohrer, and Prabal Dutta. "Demo Abstract: Applications on the Signpost Platform for City-Scale Sensing". In: *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks*. IPSN'18. New York, NY, USA: ACM, Apr. 2018. Acceptance: 28 / 32 (88%). **Best Demo Runner Up.**

[32] Joshua Adkins, Bradford Campbell, Branden Ghena, Neal Jackson, **Pat Pannuto**, and Prabal Dutta. "The Signpost Platform for City-Scale Sensing". In: *TerraSwarm 2017 Annual Review*. TerraSwarm'17. Berkeley, CA, USA, Oct. 2017. **David Wessel Best Demo Award.**

[33] Benjamin Kempke, **Pat Pannuto**, Bradford Campbell, and Prabal Dutta. "SurePoint: Exploiting Ultra Wideband Flooding and Diversity to Provide Robust, Scalable, High-Fidelity Indoor Localization". In: *Proceedings of the 14th ACM Conference on Embedded Networked Sensor Systems*. SenSys'16. Stanford, CA, USA, Nov. 2016.

[34] **Pat Pannuto**. "Accessors and the RoboCafé: Interoperability in the Internet of Things". In: *Twelfth International Nanotechnology Conference on Communication and Cooperation*. INC12. Leuven, Belgium, May 2016. **Outstanding Poster Award.**

[35] Benjamin Kempke, **Pat Pannuto**, Bradford Campbell, Joshua Adkins, and Prabal Dutta. "PolyPoint: High-Precision Indoor Localization with UWB". In: *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*. SenSys'15. Soeul, Republic of Korea, Nov. 2015.

[36] **Pat Pannuto**, Michael P Andersen, Tom Bauer, Bradford Campbell, Amit Levy, David Culler, Philip Levis, and Prabal Dutta. "Poster Abstract: A Networked Embedded System Platform for the Post-Mote Era". In: *Proceedings of the 12th ACM Conference on Embedded Networked Sensor Systems*. SenSys '14. Memphis, Tennessee, USA: ACM, 2014.

[37] Ye-Sheng Kuo, **Pat Pannuto**, and Prabal Dutta. "Demo — Luxapose: Indoor Positioning with Mobile Phones and Visible Light". In: *The 20th Annual International Conference on Mobile Computing and Networking*. MobiCom '14. Maui, Hawaii, USA, Sept. 2014.

[38] Ye-Sheng Kuo, **Pat Pannuto**, and Prabal Dutta. "Demo — Luxapose: Indoor Positioning with Mobile Phones and Visible Light". In: *1st ACM Workshop on Visible Light Communication Systems*. VLCS '14. Maui, Hawaii, USA, Sept. 2014.

[39] **Pat Pannuto**, Yoonmyung Lee, ZhiYoong Foo, David Blaauw, and Prabal Dutta. "Demo: M3: A Mm-scale Wireless Energy Harvesting Sensor Platform". In: *Proceedings of the 1st International Workshop on Energy Neutral Sensing Systems*. ENSSys '13. Rome, Italy: ACM, Nov. 2013, 17:1–17:2. ISBN: 978-1-4503-2432-8. DOI: 10.1145/2534208.2534225.

[40] **Pat Pannuto**, Bradford Campbell, and Prabal Dutta. "GATD: A Robust, Extensible, Versatile Swarm Dataplane". In: *The First International Workshop on the Swarm at the Edge of the Cloud*. SEC '13. Montreal, Quebec, Canada, 2013.

[41] Ye-Sheng Kuo, **Pat Pannuto**, and Prabal Dutta. "Demo: Floodcasting, a Data Dissemination Service Supporting Real-time Actuation and Control". In: *Proceeding of the 11th Annual International Conference on Mobile Systems, Applications, and Services*. MobiSys '13. Taipei, Taiwan: ACM, June 2013, pp. 489–490. ISBN: 978-1-4503-1672-9. DOI: 10.1145/2462456.2465697.

[42] **Pat Pannuto**, Prabal Dutta, Bradford Campbell, Samuel DeBruin, Trey Grunnagle, William Huang, Ben Kempke, Ye-Sheng Kuo, Andrew Robinson, Aaron Schulman, Maya Spivak, and Lohit Yerva. "Platforms and Protocols for Emerging Wireless Systems". In: Future of Mobile Computing Workshop. Mountain View, California: Google, 2012.

[43] **Pat Pannuto**, Yoonmyung Lee, Ben Kempke, Dennis Sylvester, David Blaauw, and Prabal Dutta. "Demo: Ultra-constrained sensor platform interfacing". In: *Proceedings of the 11th international conference on Information Processing in Sensor Networks*. IPSN '12. Beijing, China: ACM, Apr. 2012, pp. 147–148. ISBN: 978-1-4503-1227-1. DOI: 10.1145/2185677.2185721.