Research Statement **Pat Pannuto** **ppannuto@berkeley.edu**

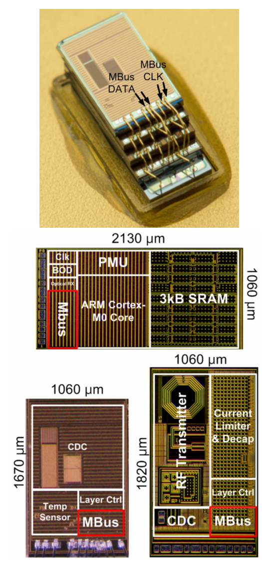
The goal of my research is to dramatically increase the reach of the digital world into the physical world. My work identifies opportunities for systems-based solutions that enable the study of broad classes of phenomenon that were previously unable to be measured: in-body physiology, fine-grained interaction behavior of large social groups, and country-scale estimates of power grid performance. Core contributions include the discovery of fundamental architectural insights that enabled the world's smallest computer,[1] the creation of a new research area by redefining the smartphone camera as a communication endpoint and sensor, and the invention of methods for the generation, manipulation, and recovery of ultra wideband signals, which pave the way to localize every physical thing.

As an embedded systems researcher, I have broad reach across traditional disciplines. My work has been recognized with awards in computer architecture, wireless communication, and networking. Additional major projects have made contributions to mobile computing, operating systems, and development engineering.

Enabling Micro-Scale Systems.

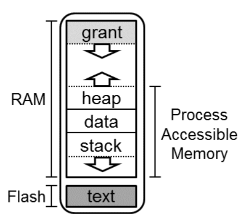
Shrinking computers expands the reach of computing. Medical sensors today require invasive implantation or bulky catheters, but a cubic-millimeter, energy-harvesting monitor could last a lifetime and would be installed with an injection no more burdensome than a vaccination. However physical scaling of computers today is limited by challenges in the formulation, powering, and interfacing of micro-scale systems.

MBus: The USB of Smart Dust. I/O has become the limiting factor in scaling computing. Existing techniques for system synthesis can no longer support the severely limited area (I/O real estate) and volume (energy capacity) of micro-scale systems. To enable modular, composable micro-scale systems, I led the design of MBus, a new chip-to-chip interconnect for the resource-constrained computing class [19]. MBus recognizes that as the cost of compute continues to fall, systems will become more modular and distributed, which motivates shifting power management into the interconnect itself. Permitting chips that are not in use to power off completely eliminates both dynamic and static leakage during inactivity, which is critical for realizing micro-scale system energy budgets. MBus ameliorates the circuits challenges of frequent cold-booting by providing a deterministic, stable power-on sequence for each chip. MBus addresses the systems concern of distributed state management by providing a "power-oblivious" communication primitive, which automatically powers chips when needed. It also offers an adaptive addressing scheme, enables multi-master operation, facilitates broadcast transmissions, supports data-independent communication, and provides efficient message acknowledgments.



A millimeter-scale system comprised of processor, temperature sensor, and wireless radio, interconnected with MBus.

IEEE Micro recognized MBus as a Top Pick in Computer Architecture in 2016 [20]. MBus has been integrated in over two dozen chips and serves as the interconnect for a startup commercializing smart dust technology.[2]



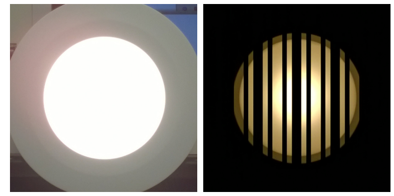
Grants use memory allocated to a process. This enables the kernel to be dynamic on behalf of processes, without risking kernel stability.

Tock. As systems shrink, they become more difficult to physically access, which creates an incentive for them to endure the lifetime of their environment. This demands robustness and adaptability beyond previously existing embedded operating systems. To enable safe, multi-tenant operation for embedded systems, we developed Tock [16]. Tock introduces "grants," a mechanism to safely allow selective dynamic allocation of kernel resources from process memory, in order to balance the stability of a statically allocated kernel with the dynamism required by multiprocessing. Recently, I have been investigating how to expand Tock's safety and correctness promises to include energy policies by using language features to encapsulate shared peripheral access and automate power management.[3]

Visible Light Communication. As the ecosystem of micro-scale systems grew, one unexpected challenge was how to interface, bootstrap, and program a system that is too small to plug anything into. Mask ROM is a standard solution, but its inflexibility compromises the modularity otherwise just gained from MBus. Instead, we developed a novel optical programming interface for wireless control [15]. Inspired by the utility for micro-scale systems, we investigated the

[1] The Michigan Micro Mote, on display at the Silicon Valley Computer History Museum.
[2] http://cubeworks.io/
[3] https://www.tockos.org/blog/2018/peripheral-management/

applicability of visible light communication for a wide range of applications, collectively called "software-defined lighting" [12]. Doing a deep dive of the many application scenarios led us to build Luxapose, the first smartphone-based localization system to offer 90th percentile position error of 16 cm and heading error of 9° using COTS phones and trivially modified COTS LED lighting [13]. By demonstrating the digital communication capacity of rolling shutter CMOS cameras and presenting the insight that a 2-D imager is inherently an angle-of-arrival sensor, Luxapose galvanized a new subfield of research in smartphone cameras-as-sensors and has over 300 citations to date.

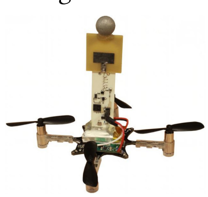


Modulated data on lights is imperceptible to humans but can be recovered by sensors and imagers.

Accessing and Utilizing the Ultra Wideband Channel.

Ultra wideband (UWB) provides robustness to multipath fading that challenges traditional narrowband radios without the complexity and directionality of millimeter-wave systems. UWB enables sub-nanosecond time synchronization and centimeter-accurate distance estimation, powerful physical world sensing primitives. Yet, challenges in the generation and recovery of UWB signals (as well as regulatory constraints) have historically limited experimental access to bulky, costly, or custom ASIC solutions.

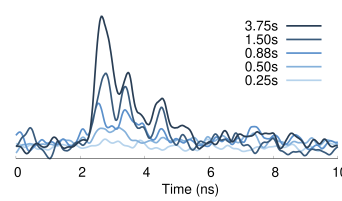
Harmonium: Ultra Wideband Generation and Recovery. The Harmonium family of work reifies the potential of UWB by making the generation and recovery of UWB signals accessible. Historically, circuits to generate sharp enough and short enough pulses to directly produce UWB signals required niche parts like step recovery diodes or complex design elements like microstrip filters. To generate UWB signals, we first avoided direct impulse generation and considered an adaptation of narrowband radios, mixing their output with an oscillator, however this proved inefficient and noisy [6]. We then designed a revised impulse generation circuit made of inexpensive, common components that was able to produce 275 ps pulses (7 GHz of bandwith) [8]. Finally, to better support resource-constrained devices we investigated pulse shaping with modern VLSI techniques to drive down transmitter energy, realizing a 1 mW transmitter [17].



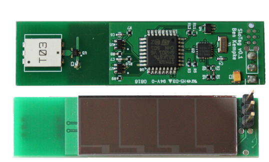
Harmonium enables high-fidelity, "through-the-walls" tracking of fast-flying micro quadrotors less than a decimeter across.

Recovering UWB is more challenging. Directly measuring gigahertz of bandwith requires gigasample per second ADCs. Time domain sampling, used by most impulse radars, requires a sampling mixer, a niche and inaccessible component. We show that a conventional narrowband radio can be used to recover UWB pulses via bandstitching, a technique that measures the UWB channel in narrowband pieces and then recombines these pieces in the frequency domain to yield the time domain signal [6, 8, 17]. We then use these UWB primitives to craft a new best-in-class localization system, demonstrating the first system capable of real-time, non-visual-based tracking of micro quadrotors [8, 17].

Slocalization: Ubiquitous Localization Realized. With Slocalization, I take a major step towards providing location information for all physical things, necessary to any application reliant on physical context. Slocalization enables through-wall, decimeter-accurate, concurrent localization of millions of batteryless devices in warehouse-scale (30 m+) complex indoor environments [18]. The observation that inspires Slocalization is that most things do not move, and many others, like keys or warehouse assets, are "nomadic," stationary except for occasional migration. This allows us to trade off latency for energy, targeting the long tail of devices. The core idea then is to build a system with the best localization (UWB) and most efficient communication (backscatter) technology. The challenge is to recover the signals from tags when UWB regulations curtail transmission power and backscatter increases path loss from quadratic to quartic. In Slocalization, we show that careful design of the signal allows integration over very long windows of time, which allows receivers to pull the signal above the noise floor and enables wide area localization for less than a microwatt. Empirically, we demonstrate that just under fifteen minutes of integration is able to find a tag at the center (worst case) of a thirty meter room.



Long-term integration raises a backscattered UWB signal out of the noise, which enables precise estimation of the signal arrival time and ultimately tag location.

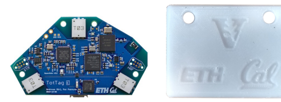


The Slocalization tag requires less than one microwatt, which allows operation with just 5 cm^2 of indoor photovoltaics.

This work was one of two best paper finalists at IPSN'18.

Applications are, of course, the whole point.

In many cases, the development, deployment, and management of a sensing system requires a dedicated technical team, which limits the reach of sensing. In addition to designing new mechanisms for measuring the physical world, my research aims to evaluate and expand the accessibility of sensing technology and thereby bolster the capabilities of domain scientists and application designers alike. This aims to serve as a force multiplier, centering not on individual deployments but rather on the principles required to enable wide-area uptake of both new and established sensing technology. Deployment-oriented work has afforded me deep interdisciplinary opportunities, including projects with economists, epidemiologists, physicians, and psychologists [1, 2, 4, 9, 10, 11].



One platform enables both measuring long-term social interaction and real-time tracking of quadrotors in flight.

PolyPoint, SurePoint, and TotTernary: Bespoke, Reliable Localization. Position information spans a very broad class of applications with a diverse array of system requirements—accuracy, precision, latency, tag or anchor size, weight, power, deployability, reliability, lifetime, and more. This breadth has afforded a wealth of localization research but has resulted in comparatively few deployed systems. Our PolyPoint project suggests that the missing elements are accuracy and deployability and realizes one of the first decimeter-accurate RF-based systems [7]. However, one severe outlier dropped PolyPoint from first to third place in the 2015 Microsoft Indoor Localization Competition [3]. The next generation, SurePoint, then suggests that it is reliability—achieving 99th percentile (rather than median) decimeter-accurate ranging with over 99.9% data reception rate—and scalability—demonstrating constructive interference for the first time in the ultra wideband channel [5]. With TotTernary, we suggest there is no one thing that will serve all demands [2]. Rather, localization applications vary in their accuracy, lifetime, latency, and deployment needs. These competing considerations can be parameterized and expressed as constraints that automatically adapt an underlying protocol, which enables pareto-optimal design- and run-time adaptation by application designers.

Continuous operation over even just a few months resulted in catastrophic failure for eight of the sixteen deployed phones.

PlugWatch: The Smartphone is Not a Sensor Network. A common requirement for sensor deployments is the collection and transport of data from the measurement site to some backend for storage and processing. This requires the development and deployment of gateway hardware to bridge sensors and the internet at large. The proliferation of smartphones has the potential to be these gateways. These are devices with a rich programming environment, mature application management frameworks, copious wireless connectivity, a diverse array of peripheral sensors, and the physical reliability of a mass-produced commercial product. Shouldn't a smartphone make a perfect gateway? However, when we attempted to do just this, and used smartphones as gateways for a power metering application in Tanzania, even a micro-deployment of just sixteen phones failed [10]. Reconsidering the smartphone, each of its capabilities relies on a hidden dependency of frequent interactions between a phone and its user. When recast as an unsupervised platform targeting machine-to-machine interactions, the pervasive micro-managing of phones by their users is revealed and assumptions of application reliability, platform stability, networking capability, peripheral support, and even physical robustness are all revealed to be false. Looking to the future, we see that the same questions that underlie the separation of desktop and cloud, those that in part have driven the transitions from multiprocessing to virtual machines to containerization, beset mobile phones: Can a single environment provide optimal performance for both resource-conscious, multi-tenant, highly interactive contexts and resource-rich, single-tenant, non-interactive contexts, or is a new design required to broaden the application reach of mobile computing?

Future Directions.

I look for opportunities to cut across traditional boundaries and pierce abstractions to enable new classes of systems and applications. To pursue such transversal paths requires deep, broad, and collaborative work; I have co-authored works with over forty different individuals from nine different institutions across four continents. These projects emerged from opportunities in devising or creating systems to measure key phenomena that could not previously be measured. While this is a broad scope, there are a few considerations that drive my current thinking.

Smart Dust and Hybrid Sensors. It is time to finally realize the Smart Dust vision. With the availability of hardware, achieved in the last decade, it is now time to explore the systems challenges, as Kahn, Katz, and Pister implored in 1999,[4] but with a firm grip on what is possible and what remains hard. Smart Dust will further exacerbate the gateway problem, demanding bridges to the internet at large. Dust will not permit human visitation or monitoring of every device, and thus requires management and robustness beyond existing systems. How shall we debug systems too small to attach wires? How do we assign, label, and recover identifiers to distinguish one device from another?

[4] J. M. Kahn, R. H. Katz, and K. S. J. Pister. Next century challenges: Mobile networking for "Smart Dust". MobiCom '99.

It is also time to leverage the components of Smart Dust available today in more traditional systems. Not every sensor needs to be, nor should it be, millimeter-sized. However, both prototype smart dust and traditional "mote-class" devices use the same ARM Cortex M0 processor (albeit with even less memory). Peripherals like nanowatt sleep timers or thresholded temperature, pressure, or motion sensors are available today. With dust components, we can drop the resource utilization of traditional embedded devices by orders of magnitude, which will invite new tradeoffs and architectures for wireless sensor networks and open new vistas in the IoT landscape.

A Trillion Things. Projections for the IoT announce visions of investments and devices into the trillions, some suggest by as early as 2020, without many limitations on expected growth. Ambitious estimates place the total number of networked devices in the world today in the tens of billions. How will our everyday systems fail when faced with orders of magnitude more devices, potentially all at once? We have seen already today that the heterogeneity of devices and interfaces impede generic applications and ecosystem adoption, which requires new frameworks for interacting with them [21]. How will individuals manage devices when the number of devices vastly outnumbers the number of individuals, accelerating a trend that began more than a decade ago?

Revisiting the Storage, Communication, and Computation Tradeoff in the Era of Cloud and Edge Computing. For the last several decades, it has been more energy efficient to push computation to the edge than to communicate raw data. Recently, however, the energy advancements for computation have slowed as we approach the limits of frequency and voltage scaling for CMOS.[5] Particularly for low data-rate applications or those amenable to specialty radios, the energy gap is now shrinking rather than growing, inviting reconsideration of where we place computation in resource-constrained pipelines for future architectures. At the same time, the gap remains large today, and there is much to be done with existing systems. The varying rates of advancement in sensor, processing, storage, and communication technology have resulted in systems with megasample per second frontends, feeding processing with 50–100 MHz clocks, that have only hundreds of kilobytes of SRAM, yet gigabytes of flash storage, and aggressively duty-cycled wireless links with effectively single-digit Kbps throughputs. While there is great potential for machine learning to extract insights from these new data streams, today edge ML stops at the gateways. We can neither collect the full data from sensors nor can we push whole networks into mote-class devices. How do heterogeneous networks change as the underlying computing resources become still orders of magnitude further removed from the cloud? How do we train networks that may never be able to offload full-fidelity raw data?

Access to Research and Research Artifacts.

To the extent that it is in my control, all publications are made freely available and all software and hardware artifacts are released as open source under permissive licenses:

- Projects Discussed in this Statement:
  - MBus: https://github.com/mbus/mbus
  - Luxapose: https://github.com/lab11/vlc-localization
  - Tock: https://github.com/tock/
  - Harmonium: https://github.com/lab11/fast-square
  - Slocalization: https://github.com/lab11/slocalization
  - PolyPoint, SurePoint: https://github.com/lab11/polypoint
  - TotTernary: https://github.com/abiri/totternary
  - PlugWatch: https://github.com/lab11/PlugWatch
    - PlugWatch is an offshoot of the greater GridWatch project, which aims to realize fine-grained country-scale grid monitoring. For more on GridWatch, please visit http://grid.watch.
    - The PowerWatch project addresses the concerns raised by PlugWatch with a custom hardware platform and is currently deployed in hundreds of homes in Accra, Ghana, as well as pilots in Nigeria and Venezuela.
    - The Open INcentive Kit [9] supports these deployments with an automated, auditable, reliable, and reproducible incentive system.

[5] S. Hanson, B. Zhai, K. Bernstein, D. Blaauw, A. Bryant, L. Chang, K. Das, W. Haensch, E. Nowak, D. Sylvester, "Ultra-Low Voltage Minimum Energy CMOS," IBM Journal of Research and Development, Vol. 50, No. 4/5, July/September 2006.

- Additional Major Projects
  - M-ulator: https://github.com/lab11/M-ulator
    Extensible simulator for ARM Cortex M0/M3 including record and replay. With supporting hardware, it allows in-circuit emulation, which enables a mixture of hardware and soft cores. It is further used in support of undergraduate courses to promote understanding of instruction encoding, architectural operation, and memory-mapped I/O.
  - Signpost [1]: https://github.com/lab11/signpost
    A modular city-scale sensing platform. The Signpost furnishes the key resources necessary to support multiple, pluggable sensor modules while providing fair, safe, and reliable sharing in the face of dynamic energy constraints.
  - Accessors [21]: https://github.com/lab11/accessors
    Accessors are a method for abstracting the complicated and diverse I/O interfaces present in real-world devices and systems. Accessors allow bundling standardized interfaces to common devices (e.g. lights, audio equipment, doors) with actual code that can access these interfaces. This abstraction enables higher level applications to interact with the physical world without having to directly interface with the myriad of protocols present in real-world devices.
  - µSDR [14]: https://github.com/lab11/uSDR
    The µSDR is a project aimed to improve the price, power, and portability of software radios, with an emphasis on technologies around the 2.4 GHz ISM band. µSDR costs a little over $100 at scale, can power itself via PoE or run continuously for nearly 8 hours on a pair of AA batteries, and supports full 802.15.4e.
  - Opo [4]: https://github.com/lab11/opo
    Opo is a face-to-face interaction sensor, able to characterize face to face interactions with 5 cm accuracy and 2 s temporal fidelity while maintaining a week-long battery life on a relatively small (110 mAh) battery.

References

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

[2] TotTernary: A localization platform for social interaction studies
Andreas Biri
Under Submission. Advised by **Pat Pannuto**. Masters Thesis. Computer Engineering, Networks Laboratory, Department of Information Technology, and Electrical Engineering, ETH Zürich, 2018.

[3] DecaWave: Exploring State of the Art Commercial Localization
Bradford Campbell, Prabal Dutta, Benjamin Kempke, Ye-Sheng Kuo, and **Pat Pannuto**
Microsoft Indoor Localization Competition. 2015.
Third Place in Infrastructure-Based Systems.

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

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

[6] Harmonia: Wideband Spreading for Accurate Indoor RF Localization
Benjamin Kempke, **Pat Pannuto**, and Prabal Dutta
SIGMOBILE Mobile Computing and Communications Review. MC^2R 18.3 (2015), pp. 19–25.
Invited Paper.

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

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

[9] The Open INcentive Kit (OINK): Standardizing the Generation, Comparison, and Deployment of Incentive Systems
Noah Klugman, Santiago Correa, **Pat Pannuto**, Matthew Podolsky, Jay Taneja, and Prabal Dutta
The Tenth International Conference on Information and Communication Technologies and Development. ICTD'19. 2019.
Acceptance: 22 / 74 (30%).

[10] Experience: Android Resists Liberation from Its Primary Use Case
Noah Klugman, Veronica Jacome, Meghan Clark, Matthew Podolsky, **Pat Pannuto**, Neal Jackson, Aley Soud Nassor, Catherine Wolfram, Duncan Callaway, Jay Taneja, and Prabal Dutta
The 24th Annual International Conference on Mobile Computing and Networking. MobiCom'18. 2018.
Acceptance: 42 / 187 (22%).

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

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

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

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

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

[16] Multiprogramming a 64kB Computer Safely and Efficiently
Amit Levy, Bradford Campbell, Branden Ghena, Daniel B. Giffin, **Pat Pannuto**, Prabal Dutta, and Philip Levis
Proceedings of the 26th Symposium on Operating Systems Principles. SOSP'17. 2017, pp. 234–251.
Acceptance: 17%.

[17] Harmonium: Ultra Wideband Pulse Generation with Bandstitched Recovery for Fast, Accurate, and Robust Indoor Localization
Pat Pannuto, Benjamin Kempke, Li-Xuan Chuo, David Blaauw, and Prabal Dutta
ACM Transactions on Sensor Networks. TOSN'18 14.2 (2018), 11:1–11:29.
Invited Paper.

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

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

[20] MBus: A System Integration Bus for the Modular Micro-Scale Computing Class
Pat Pannuto, Yoonmyung Lee, Ye-Sheng Kuo, ZhiYoong Foo, Benjamin Kempke, Gyouho Kim, Ronald G. Dreslinski, David Blaauw, and Prabal Dutta
IEEE Micro: Special Issue on Top Picks from Computer Architecture Conferences 36.3 (2016), pp. 60–70.
Top Pick in Computer Architecture.

[21] A Modular and Adaptive Architecture for Building Applications with Connected Devices
Pat Pannuto, Wenpeng Wang, Prabal Dutta, and Bradford Campbell
The 1st IEEE International Conference on Industrial Internet. ICII'18. 2018.
Invited Paper.