

# Paul Schmitt

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## Research Interests

My research focuses on networked systems architecture; protocol design; privacy; traffic inference and performance analysis; and scalable Internet measurement. My research goals are to design systems and techniques to improve network and protocol performance, enhance network user privacy, and offer insight into network and application performance—without sacrificing privacy—to network operators in order to increase network availability and performance. My research tackles problems using a first principles approach. My work achieves impact through the design, implementation, deployment, and commercialization of fundamentally new architectures, systems, and protocols in practice; employing a “dirty-slate” approach to networked systems research.

## Education

Degree	Year	University	Field
Ph.D.	2017	University of California, Santa Barbara Santa Barbara, CA <i>Dissertation:</i> Network Measurement and Systems for Resource-Constrained Environments <i>Advisor:</i> Elizabeth Belding	Computer Science
M.S.	2011	University of St. Thomas St. Paul, MN	Software Engineering
B.A.	2009	University of St. Thomas St. Paul, MN	Computer Science

## Employment History

Title	Organization	Years
Co-Founder and CEO	Invisv	August 2020–Present
Associate Research Scholar	Princeton University	June 2019–Present
External Fellow	UC Berkeley International Computer Science Institute	June 2019–Present
Postdoctoral Researcher	Princeton University	July 2017–June 2019
Research Assistant (Ph.D.)	University of California, Santa Barbara	2012–2017
Research Intern	UC Berkeley International Computer Science Institute	2016
Research Intern	IBM Research	2013
Network Administrator	University of St. Thomas	2006–2012

## Publications

### Conference Publications

- [1] Austin Hounsel, Paul Schmitt, Kevin Borgolte, and Nick Feamster. Can encrypted DNS be fast? In *Passive and Active Measurement Conference (PAM)*, Brandenburg, Germany, March 2021.

- [2] Shinan Liu, Paul Schmitt, Francesco Bronzino, and Nick Feamster. Characterizing service provider response to the COVID-19 pandemic in the United States. In *Passive and Active Measurement Conference (PAM)*, Brandenburg, Germany, March 2021.
- [3] Francesco Bronzino, Paul Schmitt, Sara Ayoubi, Guilherme Martins, Renata Teixeira, and Nick Feamster. Inferring Streaming Video Quality from Encrypted Traffic: Practical Models and Deployment Experience. In *ACM SIGMETRICS*, Boston, Massachusetts, USA, June 2020.
- [4] Austin Hounsel, Kevin Borgolte, Paul Schmitt, Jordan Holland, and Nick Feamster. Comparing the Effects of DNS, DoT, and DoH on Web Performance. In *The Web Conference (WWW)*, Taipei, Taiwan, April 2020.
- [5] Kevin Borgolte, Tithi Chattopadhyay, Nick Feamster, Mihir Kshirsagar, Jordan Holland, Austin Hounsel, and Paul Schmitt. How DNS over HTTPS is Reshaping Privacy, Performance, and Policy in the Internet Ecosystem. In *Research Conference on Communications, Information and Internet Policy (TPRC)*, Washington, DC, September 2019.
- [6] Paul Schmitt, Anne Edmundson, and Nick Feamster. Oblivious DNS: Practical Privacy for DNS Queries. In *Symposium on Privacy Enhancing Technologies (PETS)*, Stockholm, Sweden, July 2019.
- [7] Vivek Adarsh, Paul Schmitt, and Elizabeth Belding. MPTCP performance over heterogenous sub-paths. In *International Conference on Computer Communication and Networks (ICCCN)*, Valencia, Spain, July 2019.
- [8] M. Zheleva, T. Larock, P. Schmitt, and P. Bogdanov. Airpress: High-accuracy spectrum summarization using compressed scans. In *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Santa Clara, California, USA, October 2018.
- [9] Paul Schmitt, Francesco Branzino, Renata Teixeira, Tithi Chattopadhyay, and Nick Feamster. Enhancing Transparency: Internet Video Quality Inference from Network Traffic. In *Research Conference on Communications, Information and Internet Policy (TPRC)*, Washington, DC, September 2018.
- [10] Carleen Maitland, Richard Caneba, Paul Schmitt, and Tom Koutsy. A Cellular Network Radio Access Performance Measurement System: Results from a Ugandan Refugee Settlements Field Trial. In *Research Conference on Communications, Information and Internet Policy (TPRC)*, Washington, DC, September 2018.
- [11] Mariya Zheleva, Petko Bogdanov, Timothy Larock, and Paul Schmitt. AirVIEW: Unsupervised transmitter detection for next generation spectrum sensing. In *IEEE INFOCOM*, Honolulu, Hawaii, USA, April 2018.
- [12] Paul Schmitt, Daniel Iland, Elizabeth Belding, and Mariya Zheleva. Phonehome: Robust extension of cellular coverage. In *International Conference on Computer Communication and Networks (ICCCN)*, Waikoloa, Hawaii, USA, August 2016.
- [13] Paul Schmitt, Daniel Iland, Elizabeth Belding, Brian Tomaszewski, Ying Xu, and Carleen Maitland. Community-level access divides: A refugee camp case study. In *International Conference on Information and Communications Technologies and Development (ICTD)*, Ann Arbor, Michigan, USA, June 2016.
- [14] Paul Schmitt, Daniel Iland, Mariya Zheleva, and Elizabeth Belding. Hybridcell: Cellular connectivity on the fringes with demand-driven local cells. In *IEEE INFOCOM*, San Francisco, California, USA, April 2016.
- [15] Paul Schmitt, Morgan Vigil, and Elizabeth Belding. A study of MVNO data paths and performance. In *Passive and Active Measurement Conference (PAM)*, Heraklion, Crete, Greece, March 2016.

- [16] Paul Schmitt, Ramya Raghavendra, and Elizabeth Belding. Internet media upload caching for poorly-connected regions. In *ACM Symposium on Computing for Development (DEV)*, London, United Kingdom, December 2015.
- [17] Mariya Zheleva, Paul Schmitt, Morgan Vigil, and Elizabeth Belding. The increased bandwidth fallacy: Performance and usage in rural Zambia. In *ACM Symposium on Computing for Development (DEV)*, Cape Town, South Africa, December 2013.

## Journal Publications

- [18] Paul Schmitt, Daniel Iland, Mariya Zheleva, and Elizabeth Belding. Third-party cellular congestion detection and augmentation. *IEEE Transactions on Mobile Computing*, 18(1), 2019.
- [19] Paul Schmitt, Daniel Iland, and Elizabeth Belding. Smartcell: Small-scale mobile congestion awareness. *Communications Magazine*, 54(7):44–50, July 2016.
- [20] Mariya Zheleva, Paul Schmitt, Morgan Vigil, and Elizabeth Belding. Internet bandwidth upgrade: Implications on performance and usage in rural Zambia. *Information Technologies & International Development*, 11(2), 2015.

## Workshop Publications

- [21] Francesco Bronzino, Elizabeth Culley, Nick Feamster, Shinan Liu, Jason Livingood, and Paul Schmitt. Interconnection changes in the United States. In *Internet Architecture Board (IAB) COVID-19 Workshop*, 2020.
- [22] Paul Schmitt, Anne Edmundson, Allison Mankin, and Nick Feamster. Oblivious DNS: Practical Privacy for DNS Queries. In *IRTF Applied Networking Research Workshop (ANRW)*, Montreal, Quebec, Canada, July 2019.
- [23] Austin Hounsel, Kevin Borgolte, Paul Schmitt, Jordan Holland, and Nick Feamster. Analyzing the Costs (and Benefits) of DNS, DoT, and DoH for the Modern Web. In *IRTF Applied Networking Research Workshop (ANRW)*, Montreal, Quebec, Canada, July 2019.
- [24] Paul Schmitt and Elizabeth Belding. Low on air: Inherent wireless channel capacity limitations. In *ACM Workshop on Computing Within Limits (LIMITS)*, Santa Barbara, California, USA, June 2017.
- [25] Thomas Pötsch, Paul Schmitt, Jay Chen, and Barath Raghavan. Helping the lone operator in the vast frontier. In *ACM SIGCOMM Workshop on Hot Topics in Networking (HotNets)*, Atlanta, Georgia, USA, November 2016.
- [26] Paul Schmitt and Elizabeth Belding. Navigating connectivity in reduced infrastructure environments. In *ACM Workshop on Computing Within Limits (LIMITS)*, Irvine, California, USA, June 2016.
- [27] Mariya Zheleva, Paul Schmitt, Morgan Vigil, and Elizabeth Belding. Community detection in cellular network traces. In *International Conference on Information and Communications Technologies and Development (ICTD: Notes)*, Cape Town, South Africa, December 2013.
- [28] Mariya Zheleva, Paul Schmitt, Morgan Vigil, and Elizabeth Belding. Bringing visibility to rural users in Cote d’Ivoire. In *International Conference on Information and Communications Technologies and Development (ICTD: Notes)*, Cape Town, South Africa, December 2013.
- [29] Paul Schmitt, Morgan Vigil, Mariya Zheleva, and Elizabeth Belding. Communication flow patterns in the D4D dataset. In *NetMob Session on Data for Development (D4D)*, Boston, Massachusetts, USA, April 2013.

## Submitted Publications and Works-in-progress

- [30] Francesco Bronzino, Paul Schmitt, Sara Ayoubi, Hyojoon Kim, Renata Teixeira, and Nick Feamster. Traffic refinery: Cost-aware traffic representation for machine learning in networks. *ArXiv e-prints*.
- [31] Paul Schmitt and Barath Raghavan. Pretty good phone privacy. *ArXiv e-prints*.
- [32] Jordan Holland, Paul Schmitt, Nick Feamster, and Prateek Mittal. nPrint: Standard packet-level network traffic analysis. *ArXiv e-prints*.
- [33] Austin Hounsel, Paul Schmitt, Kevin Borgolte, and Nick Feamster. D-DNS: Towards re-decentralizing the DNS. *ArXiv e-prints*.
- [34] Jordan Holland, Ross Teixeira, Paul Schmitt, Kevin Borgolte, Jennifer Rexford, Nick Feamster, and Jonathan Mayer. Classifying network vendors at Internet scale.
- [35] Sulagna Mukherjee, Srivatsan Ravi, Felipe Mansilla-Borquez, Paul Schmitt, and Barath Raghavan. The ghost trilemma.

## Theses

- [36] Paul Schmitt. *Network Measurement and Systems for Resource-Constrained Environments*. PhD thesis, University of California, Santa Barbara, June 2017.

## Books and Book Chapters

- [37] Paul Schmitt, Daniel Iland, Elizabeth Belding, and Mariya Zheleva. *Digital Lifeline? ICTs for Refugees and Displaced Persons*. MIT Press, 2018. *Chapter*: Cellular and Internet Connectivity for Displaced Populations.

## Technical Reports

- [38] Bilal Saleem, Paul Schmitt, Jay Chen, and Barath Raghavan. Beyond the trees: Resilient multipath for last-mile WISP networks. arXiv:2002.12473 [cs.NI], 2020.
- [39] Anne Edmundson, Paul Schmitt, Nick Feamster, and Jennifer Rexford. OCDN: Oblivious content distribution networks. arXiv:1711.01478 [cs.NI], 2017.
- [40] Adam Lerner, Giulia Fanti, Yahel Ben-David, Jesus Garcia, Paul Schmitt, and Barath Raghavan. Rangzen: Anonymously getting the word out in a blackout. arXiv:1612.03371 [cs.NI], 2016.
- [41] Carleen Maitland, Brian Tomaszewski, Elizabeth Belding, Karen Fisher, Ying Xu, Danny Iland, Paul Schmitt, and Amira Majid. Youth mobile phone and Internet use, January 2015, Za’atari Camp, Mafrq, Jordan. Technical report, Penn State University, State College, Pennsylvania, USA, 2015.

## Talks

- “Internet Video Quality Inference from Encrypted Network Traffic”. *NSF Workshop on Measurements for Self-Driving Networks*. Princeton, New Jersey, April 2019.
- “Internet Video Quality Inference from Encrypted Network Traffic”. *Network Programming Initiative Fall Retreat*. New York, New York, October 2018
- “ODNS: Oblivious DNS”. *DNS-OARC 28*. San Juan, Puerto Rico, March 2018.
- “Correlating Network Congestion with Video QoE Degradation - a Last-Mile Perspective”. *Workshop on Active Internet Measurements (AIMS)*. San Diego, California, March 2018.

## Selected Press

- “The Truth About Faster Internet: It’s Not Worth It”. *Wall Street Journal*. Front Page (A1) Feature. August 2019.
- “Sorry spooks: Princeton boffins reckon they can hide DNS queries” *The Register*. April 2018.
- “Oblivious DNS could protect your internet traffic against snooping” *TechRepublic*. April 2018.
- “Isolated in Zaatari camp, Syrian refugees find ways to get online” *Al Jazeera America*. July 2015.

## Teaching and Mentoring

### Teaching assistant

- Object Oriented Design and Implementation (CMPSC 32), UCSB, Spring 2013
- Network Computing (CMPSC 176b), UCSB, Winter 2013
- Object Oriented Design and Implementation (CMPSC 32), UCSB, Fall 2012

### Adjunct Instructor

- Computer Networking (CISC 370), University of St. Thomas, Spring 2012
- Operating Systems (CISC 310), University of St. Thomas, Fall 2011

### Ph.D. Student Mentorship

- **Shinan Liu.** *Summer 2020 - Present.*  
Publications: [2], [21]
- **Sulagna Mukherjee.** *Summer 2019 - Present.*  
Publications: [35]
- **Jordan Holland.** *Fall 2018 - Present.*  
Publications: [4], [5], [23], [32], [34]
- **Austin Hounsel.** *Fall 2017 - Present.*  
Publications: [1], [4], [5], [23], [33]
- **Anne Edmundson.** *Fall 2017 - Spring 2018.*  
Publications: [6], [22], [39]

## Software

### Ongoing and Maintained Software

- *Oblivious DNS* ([odns.cs.princeton.edu](https://odns.cs.princeton.edu)). We have developed a system to increase DNS privacy which (1) obfuscates the queries that a recursive resolver sees from the clients that issue DNS queries; and (2) obfuscates the client’s IP address from upper levels of the DNS hierarchy that ultimately resolve the query (i.e., the authoritative servers). ODNS operates in the context of the existing DNS protocol, allowing the existing deployed infrastructure to remain unchanged. ODNS resulted in an IETF draft (“Oblivious DNS - Strong Privacy for DNS Queries”), it has led to multiple industry-backed IETF drafts (“Oblivious DNS Over HTTPS”, “Adaptive DNS Privacy”), and its underlying techniques are present in an implementation by Cloudflare, Apple, and Fastly<sup>1</sup>.
- *PGPP*. Pretty Good Phone Privacy (PGPP) is a fundamentally new cellular network architecture that provides users with location anonymity from the cellular carrier itself. By implementing our design, a cellular carrier no longer has the ability to track and record (and subsequently monetize) individual users’ location history. Invis ([invisv.com](https://invisv.com)), a privacy-focused commercial cellular startup, leverages the PGPP architecture.

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<sup>1</sup><https://blog.cloudflare.com/oblivious-dns/>

- *nPrint* ([nprint.github.io/nprint](http://nprint.github.io/nprint)). nPrint is a standard data representation for network traffic meant to be directly usable with machine learning algorithms, replacing feature engineering for a wide array of traffic analysis problems. nPrint encodes data in a normalized, bit-aligned, space-efficient format that facilitates representation learning which automatically discovers the semantically important parts of network packets.
- *NetMicroscope* ([netmicroscope.com](http://netmicroscope.com)). We have developed a system that supports passive measurement for a wide variety of services and network scenarios based on the above requirements. The system has two components: (1) a packet processing module that measures flow statistics and tracks their state at line rate; ; and (2) a quality inference module that queries the flow cache to obtain flow statistics and derive the service quality for tracked applications. We have deployed this software in 50 user homes in the United States and France and are working with journalists to publish investigations from the tool, including how video quality relates to access ISP speed.

## Older Projects

- *HybridCell*. A system that enables coexistence between commercial and local cellular coverage to augment poorly performing infrastructure. HybridCell monitors nearby commercial cellular networks and dynamically adjusts local network usage based on the “health” of the commercial network.
- *Cellular congestion detection*. A system and algorithm for passive detection and characterization of cellular base station radio congestion. The system has been used in measurement campaigns in rural Guatemala and large refugee camps in Uganda and Jordan. Our findings allowed local organizations to approach carriers to improve connectivity.
- *AirPress*. A system that allows for one-pass spectrum characterization. AirPress employs wavelet decomposition to achieve rapid transmitter detection in low and high noise environments.
- *WISPR*. A network protocol, WISPR (Wireless Internet Service Providers with Redundancy), that enables multi-path over low-cost, heterogeneous wireless links.
- *VillageCache*. A system that transparently scrapes uploads and redelivers locally-created media in users’ web sessions without accessing the Internet bottleneck link for poorly-connected networks.

## Honors and Awards

- 2016-2017 UCSB President’s Dissertation Year Fellowship
- 2014-2015 Dean’s Fellowship, UCSB

## Service

- PC member for the International Teletraffic Congress (ITC)
- PC member for the ACM Workshop on Computing within Limits (LIMITS)
- NSF review panel 2020
- External reviewer for IEEE INFOCOM
- External reviewer for ACM MobiCom
- Reviewer for IEEE Transactions on Mobile Computing
- External reviewer for IEEE International Conference on Data Mining
- Representative on UCSB CS Graduate Student Cabinet
- PC member of the Graduate Student Workshop in Computing 2014, UCSB
- PC member of the Graduate Student Workshop in Computing 2013, UCSB