Toward a Network of Connected Things

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This installment of Research for Practice features a curated selection from Deepak Vasisht, who takes us on a tour of systems and networking for the Internet of Things. Deepak's selection spans energy harvesting to agriculture, providing a look into the future of IoT deployments and their usability.

—Peter Bailis

Over the past few years, we have started realizing the IoT (Internet of things) dream. Amazon Echo, Dash buttons, Nest cameras, Google Home, etc. have permeated our lives at home, and enterprises in various sectors such as retail, airlines, transportation and logistics have started benefiting from industrial IoT solutions. Inspired by this impetus, General Electric recently estimated that investments in industrial IoT alone would top \$60 trillion over the next 15 years.

All this growth has been fueled by years of research tackling several challenges, ranging from low-power networking to new sensor designs to security and privacy. This installment of Research for Practice presents research papers that aim: [a] to make IoT deployments

more pervasive and (b) to enable users to gain more utility from existing deployments.

Easing the cost of deployment

Zhang, P., Bharadia, D., Joshi, K., Katti, S. 2016. HitchHike: practical backscatter using commodity Wi-Fi. *Proceedings of the 14th ACM Conference on Embedded Network Sensor Systems CD-ROM (SenSys)*: 259-271; <https://dl.acm.org/citation.cfm?id=2994565>.

One of the natural challenges of large-scale networked sensor deployments is the cost of powering them up. The high power cost of communication modules leads to frequent battery replacements, which, in turn, incur large labor costs. A recent sequence of backscatter solutions aims to change that by leveraging existing radio frequency transmissions to communicate. Specifically, backscatter communication systems allow devices to modulate and reflect existing Wi-Fi transmissions, thus enabling low-power communication modules that could be powered either by harvesting ambient power or by batteries that last several years.

HitchHike is unique for two reasons. First, not only can it reflect transmissions from commodity Wi-Fi devices, its reflections can also be received and decoded by commodity Wi-Fi devices. This allows the widely prevalent Wi-Fi devices, such as your access point, to interact with the sensors at a very low cost for power. Second, HitchHike can achieve a data rate of 200 Kbps at a distance of 54 meters. This data rate is high enough for most sensors

and covers a very large area, larger than most homes and small enterprises. Going forward, HitchHike and others in this space promise to allow applications with severe power constraints, such as implantable sensors, wearables, sensors embedded in walls and bridges, etc.

Designing novel sensing mechanisms

Adib, F., Mao, H., Kabelac, Z., Katabi, D., Miller, R. C. 2015. Smart homes that monitor breathing and heart rate. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*: 837-846; <https://dl.acm.org/citation.cfm?id=2702200>.

A continuous thread of innovation in the IoT space has been the design of novel sensing mechanisms. A recent trend in this space has been monitoring health metrics such as breathing, heart rate, walking patterns, sleep stages, gait, and even emotional health in a completely contactless way. Amazon Echo or Google Home, for example, could be equipped with these capabilities, allowing users to know more about their physical and mental health.

This paper describes VitalRadio, a device that can monitor breathing and heart rate of a user without any contact with the user at distances up to eight meters, even when the user is in a different room. VitalRadio presents the basic techniques that form the foundation of a lot of the later work on monitoring various other health metrics. On a high level, VitalRadio works by analyzing the reflections of radio signals from human bodies. As humans breathe [or their hearts beat], the reflections are affected by any

minute change. VitalRadio extracts these small changes in the reflections to estimate the heart rate and breathing of individuals. While there are still some limitations on the operation of the system, like requirements for a one- to two-meter minimum separation between multiple users and quasi-static user behavior (watching TV, typing, etc.), none of these limitations is big enough to hinder mainstream health monitoring applications.

Exploiting already-deployed sensors for new services

Abari, O., Vasisht, D., Katabi, D., Chandrakasan, A. 2015. Caraoke: an e-toll transponder network for smart cities. Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication: 297-310; <https://dl.acm.org/citation.cfm?id=2787504>.

The push for IoT over the past decade has ensured that we have already deployed several billion sensors, such as toll transponders in cars, RFIDs in warehouses and restaurants, etc. These devices enable very specific functionality—automatic toll collection for cars or inventory tracking in warehouses. A key question, then, is what can be done to leverage these large deployments for more general-purpose applications?

Caraoke achieves this for e-toll transponders by using them to monitor traffic, locate and identify cars, detect speeding, and enable automated detection of empty parking spots—all without any changes to the e-toll transponders deployed on cars. Since such transponders are being used by 70-89 percent of drivers in the U.S. (depending on the state) and are seeing increased adoption worldwide, Caraoke can

play an important role in the push for smart cities where the traffic lights react to real-time traffic information, and drivers are automatically guided to empty parking spots. The fundamental contribution of Caraoke is its ability to separate simultaneous transmissions from multiple transponders using novel signal processing techniques that exploit the frequency-domain structure of the signal. Caraoke incorporates these techniques into a new reader for transponders that can be deployed on street-light poles and harvest solar energy for their operation. Going forward, such innovations in different domains can expand the utility of deployed IoT systems manifold.

Expanding IoT to “untouched” environments

Vasisht, D., Kapetanovic, Z., Won, J., Jin, X., Chandra, R., Kapoor, A., Sinha, S. N., Sudarshan, M., Stratman, S. 2017. FarmBeats: an IoT platform for data-driven agriculture. Proceedings of the 14th Usenix Symposium on Networked Systems Design and Implementation; <https://www.usenix.org/conference/nsdi17/technical-sessions/presentation/vasisht>.

While IoT has prospered in well-connected, well-powered environments such as urban homes and large enterprises, its adoption in harsher environments, without good sources of power and Internet, has been relatively low. Such environments include farming, construction, and mining—sectors that employ large sections of both the developing and the developed world. For example, even in the United States, the process of data collection in farming remains primarily manual, which limits the adoption of advanced

agricultural techniques to fewer than 20 percent of farmers.

FarmBeats attempts to tackle this challenge by focusing on the challenge of data-driven agriculture. Data-driven agricultural techniques such as precision irrigation can allow farmers to improve yields, reduce input cost, and enhance labor productivity. FarmBeats lets farmers employ these techniques by developing an end-to-end IoT platform for agriculture that enables seamless data collection from sensors, cameras, and drones.

FarmBeats uses three ideas to enable this platform. First, to enable connectivity on the farm, it uses a mix of TV white spaces (to allow long-range connectivity over several miles) and Wi-Fi (to allow interfacing with commercial sensors). Second, to deal with weather-related outages and low bandwidths, it designs an IoT gateway that sits on the farm and provides services to the farmer while creating summaries for the cloud. Finally, it leverages machine-learning techniques to combine inputs from a drone and ground sensors to provide more accurate information and reduce the requirement for sensor deployments. The paper presents results from a multiseason deployment of FarmBeats on two different farms on the two coasts of the United States.

Final thoughts

The exciting research being done in IoT systems has put us ever closer not only to developing new services, but also to gathering new data sets for consumer and enterprise applications. Combined with recent significant advances in artificial intelligence and machine learning, these data sets can drive new applications. For example, VitalRadio has

been extended to leverage novel deep-learning techniques to monitor sleep stages of a user completely passively. Researchers can also leverage new machine learning techniques as tools to design better systems. FarmBeats already shows how one can leverage AI to reduce the requirement for sensor placement and to guide the placement of sensors to maximize information.

While this scale of data presents new avenues for improvement, the key challenges for the everyday adoption of IoT systems revolve around managing this data. First, we need to consider where the data is being processed and stored—on the local edge computer or in the cloud—and what the privacy and systems implications of these policies are. Second, we need to develop systems that generate actionable insights from this diverse, hard-to-interpret data for non-tech users. Solving these challenges will allow IoT systems to deliver maximum value to end users.

Deepak Vasisht *is a PhD candidate in electrical engineering and computer science at MIT. His research is focused on wireless networks and IoT systems. He has designed, built and deployed systems that deliver ubiquitous sensing, accurate indoor positioning, enhanced communication capabilities, and new human computer interfaces. His research has been featured in the Economist, IEEE Spectrum, BBC, and CBC, among others. He is the recipient of the ACM SIGCOMM Best Paper award, a Microsoft Research PhD Fellowship, and the President's Gold Medal at IIT Delhi.*

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