Magic Is in the Airwaves

An Interview with Andrea Goldsmith about Wireless Communications and Collaborative Research

by Luke Redington

Because I am one generation too old to be a digital native, I remember the moment I first beheld the magic of cell phones. I was watching TV. It was the early days of *Law and Order*—long before the franchise became dizzy with spin-offs—back when the plots still revolved around, you know, law and order. In those days, a typical episode would include a scene like this: The two streetwise detectives sneak to the doorway of an upper West Side apartment. The older detective flanks the apartment's door; the younger detective crouches to put extra power in his kick. They look at each other. The older is about to nod to the younger when his polyester sport coat makes the sound of a phone ringing. He snatches something shaped like a small refrigerator out of his coat and presses it alongside his face. His eyebrows wrinkle. He steps back from the door and signals to his partner that they should head back to their cruiser. The older detective shoves the fridge back into his coat. "No match on the ballistics. Gotta get back to the precinct." They speed away in their boxy Crown Vic. Pure magic.

In hindsight, I recognize that the detective's cell phone seemed all the more magical because none of the characters within the story thought twice about the cell phone's novelty or mystique. They just used it and went about their official police business without breaking stride. So, in the comfort of my parent's living room, I was confronted with two unsettling questions at once: How could such a device exist? How could it seem so normal? Decades ago, science fiction author Arthur C. Clarke theorized about the second question. He posited that "Any sufficiently advanced technology is indistinguishable from magic" (2000, 2). Clarke asserts that even leading scientists feel they are witnessing something magical when they do not possess the necessary framework to debunk what they see (2000, 24–5). My thirteen-year-old framework understood conventional telephones only as the things girls never picked up to call me, so cell phones were right up there with unicorns.

Frequent use makes the magical shine wear off. Like most people —96.3% globally, says the World Bank Database (2015)—I have a cell phone. I depend on it every day without a clue how it works. I did, however, have the chance to talk to someone who does. Andrea Goldsmith knows about the magic of cell phones because she helped make it what it is today. Goldsmith holds the Stephen Harris Professorship in Stanford University's department of Electrical Engineering and founded two successful Silicon Valley companies. In our conversation, Goldsmith looked back at the trajectory of her research and noticed that unexpected turns lead her to good things. She also offered insights about what it means to remain on the edge of innovation in wireless communications. (Spoiler: It means working well with people from other academic fields.) Finally, if anyone has a crystal ball in which to see the future of wireless communications, it is Goldsmith. She mapped a future in which magic will happen everyday. Highways will monitor and guide their own traffic. Neurological disorders will be treated with simple electrical impulses. Some communications devices will consume so little energy that recharging as we know it will disappear. It is a vision of the future that draws closer each time Goldsmith describes it.

Professor Andrea Goldsmith

I. Hindsight
At about the time *Law and Order* first hit the airwaves, Goldsmith began graduate school. From the start, wireless communication technologies held her fascination. She explains:

> I went back to graduate school in 1989 when the first generation of analogue cell phones had been considered a success, and industry was moving to the standardization of the second generation. And, at that time, there were a lot of people working in cellular technology and wireless, but I could tell in the late 80's that this was going to be a really exciting field to work in. There were many open problems.

At precisely this point in the interview, the pace of Goldsmith's speech picked up considerably. In the next few sentences, she described the research questions that drew her into wireless communications, and by then, she was off to the races. I mention this not only to offer a sense of the interview experience, but because Goldsmith, like so many innovators, overflows with enthusiasm for her research. Before Goldsmith gave the plenary address at the 2014 Information Theory Society conference, she was introduced by Urbashi Mitra, a professor at the University of Southern California who collaborates with Goldsmith. Mitra described Goldsmith as "A force of nature" (ISIT 2014). I agree. My impression is that she does not multitask, exactly; it is more like she dares any one activity to take up all her bandwidth. With much gusto, Goldsmith described the research problems that fueled her enthusiasm during graduate school:

> We didn't understand fundamental capacity limits, we didn't understand how to design these systems, and so what changed in the research is that we went from having mostly wireline channels—static channels—where we had a good understanding of the Shannon limits; we knew how to achieve them or close to them, and so there wasn't a whole lot more to do—and then, BOOM, we have these wireless systems where you have all these random characteristics of the propagation. And that means that you're building a system on top of a fundamentally unreliable channel! And that opened up a new world of new theoretical challenges as well as practical challenges: How do we build these systems? So, that's what I started doing research for my PhD in, and that's still what continues to drive a lot of what I'm doing.

Let's begin at the end of this quote. From the moment Goldsmith began grad school, she has endeavored to build reliable wireless communication systems. (She has succeeded grandly, bringing you fewer dropped calls and less buffering lag during your *Law and Order* streaming binge.) Goldsmith describes the challenges inherent in building reliable wireless communications systems as both theoretical and practical because in the early 1990's, second-generation cell phone technology took hold so quickly that the only thing electrical engineers knew for sure was that everybody wanted it fast. Engineers did not know for sure how cell phone signals behave in the wild, or as Goldsmith puts it, engineers did not know "the random characteristics of the propagation." Without this theoretical knowledge, practical questions like where a cell tower should go or what frequency it should utilize remained out of reach. So Goldsmith set out to increase electrical engineers' knowledge of how much information can travel over a wireless system before so much gets lost in translation that the transmission ceases to be useful. This breaking point is called a "Shannon limit" in honor of Claude Shannon, who in 1948 set out to address practical challenges associated with long-distance telephony and ended up framing the theories that would eventually make the internet and cell phones possible.

Today, electrical engineers are not asking how to build wireless communications systems, but how to build them in the best possible way—a trick they call "optimization." Looking back on her career, Goldsmith sees optimization as a long-standing theme. In her field, optimization is now a buzzword, and as usually happens, its meaning has become less precise as an inverse function of its popularity. Todd Coleman, a bioengineering professor at UC San Diego and a collaborator with Goldsmith, has a great way of cutting through the static about this buzzword. At a 2014 conference, he said, "When you're talking about optimization, it doesn't mean anything until you describe what it is you want to optimize for the conditions and constraints in which you want something to be optimal"(2014). I mentioned this quote to Goldsmith to frame our discussion of optimization. She explained that in the context of her own research, optimization means designing communication systems with the best possible wireless channels. This inherently difficult task is made more challenging because the relevant conditions and constraints are constantly shifting. With a fiery enthusiasm I had by now come to expect, she described the new challenges that arise as conditions vary:

> The channel is changing because users are moving around; the environment may be changing; the traffic patterns of the users may be changing; they want video one minute, text another minute. So, how do you optimize the resources of the network at each time instant to meet those demands? And, that's something that drove my research at the beginning of my PhD, which was to look at the Shannon capacity of wireless channels. We knew the Shannon capacity of a static channel, but what is the capacity when the channel changes? And, the interesting thing there, in touching on Todd's point, is, there is no one answer. It depends on what you know about how the channel is changing: Do you know the channel conditions at the receiver only? Do you know them at the transmitter, so you can optimally adapt to them? So, when you talk about optimization in wireless, there are all these assumptions you need to make about the conditions in the system itself: What information is known? How do you obtain that information? Do you just assume that it's instantaneously available? Are there errors in your understanding of the state of the system? And this goes beyond just a single point to point wireless channel, but wireless networks. You know, these are very complex, dynamic systems. And, how you optimally control that complex, dynamic system is an extremely challenging problem.

Goldsmith's description of these challenges may raise more questions for you than it answers. No worries. An analogy may help. I didn't mention this analogy during the interview, but in retrospect, I think it fits: Optimizing a wireless channel resembles running a cost-efficient college cafeteria. On the surface, the task is simple: Buy the right amount of food supplies and then prepare the right number of meals each day. In practice, though, making cost-efficient decisions requires accurate predictions of shifting variables: What percentage of students will actually wake up in time for hot breakfast? Will the lunch crowd continue to supplement pizza with Frosted Flakes and Fruity Pebbles at an alarmingly high rate? How sharply will consumption of Rice Krispy treats increase during finals week? As you probably gleaned from Goldsmith's quote, some variables can be accommodated, but others must be constrained. If everyone near a single cell tower wanted to send a brief text message at once, the tower might be able to handle it. But if the same group all wanted to simultaneously stream video through their phones, a wireless traffic jam would ensue. In deciding how many towers to build, wireless service providers must strike a balance between too few (which would result in drops and lags) and too many (which would run up price disproportionately to performance). And, like cafeteria managers, they must strike this balance by predicting human preference. Goldsmith's work has made these predictions easier. New technologies stemming from her theoretical research have boosted the capacities of wireless networks, thus providing more and better options to those designing the networks.

II. Insight

Over the last few decades, Goldsmith's work on wireless channel optimization and a dazzling array of other topics have made her a fixture in the field of electrical engineering. Her trajectory seemed clear: Keep doing award winning research within her academic discipline and training her students to do likewise. Goldsmith has stayed this course, but her career path has also branched in some unexpected directions. In 2010, Goldsmith got in on the ground floor of the Center for Science of Information (CSoI), a National Science Foundation research consortium. Many of its researchers share Goldsmith's interest in wireless communications, but they all share an interest in information itself, including how to define it, how to transmit it, and how to store it securely. Because CSoI is bound together by an interest in information rather than the research agenda of any single academic discipline, it has become remarkably eclectic. CSoI is thickly populated, for example, with biologists. What's the connection? Well, for centuries, biologists have known that nerve cells have a lot in common with electrical wiring and circuits. In 1791, Luigi Galvani published his discovery that freshly severed frog legs still kick when zapped with electricity (Piccolino 2008, 338–9). Galvani's discovery gave rise to the theory that the nervous system functioned as an intricate network of nerve cells bound together in long, continuous, complex chains (Hamburger 1980, 600–1). For the next century, neurologists based their experiments on this view of the nervous system and made made major breakthroughs. But in the 1890's a Spanish scientist dared to bother this theory with an astounding fact: Nerves don't actually touch one another. In the 1890's, Santiago Ramón y Cajal proved that a small gap exists between nerve cells wires which he called "synapses" (Hamburger 1980, 601). Synapses indeed conduct electric current and send signals, but not in a way analogous to a network of electrical wires and circuits. It is more like a wireless network. Enter Andrea Goldsmith.

CSoI made it possible for Goldsmith and the aforementioned Todd Coleman to collaborate on a variety of projects that study the inner workings of neural networks. By applying information theory to neurology, Coleman's lab has produced, among many other things, a brain-reading hat that allows its wearer to fly a drone just by thinking about the direction the drone should go (Coleman 2014; Abdullah Akce, Miles Johnson, and Timothy Bretl 2010). Through their CSoI-sponsored collaboration, Coleman and Goldsmith bent their expertise toward the brain itself. The result was a project that has already had remarkable success using small electrical currents to treat epileptic seizures. More and more people became spellbound by their work. Goldsmith's graduate students, mostly electrical engineers, regularly make forays into biology and neurology. Joseph Parvizi, a professor at Stanford's medical school, now works closely with Goldsmith on the epilepsy project. During the interview, Goldsmith pulled back the curtain on the inter-disciplinary dynamics that make this collaboration successful: "Scientists generally observe a phenomenon and try to come up with an explanation for it; engineers try to engineer things." True that. So well acquainted are engineers with the tools of their trade that sometimes they can help scientists in their quest to observe and explain phenomena. Goldsmith shared two examples from her collaboration with Parvizi:

> I gave a talk to his research group on communication for dummies and he gave a talk on neuroscience for dummies to my research group. So, in the neuroscience talk, he was explaining how an epileptic fit happens. So, he says, "Signals associated with a set of neurons in a part of the brain start oscillating. And then that oscillation moves to neurons in another part of the brain, and *those* signals start oscillating, and then they move to neurons in *another* part of the brain, and *those* signals start oscillating, and, eventually, if you have enough oscillations, you go into an epileptic seizure. And, so I said, "I know this is a really dumb question, but can't you just put like a low pass filter or band pass filter in instead of using drugs to block signals from moving to different parts of the brain?" and he said, "What's a low pass filter?"

Of course, Goldsmith and Parvizi are not asking dumb questions. The short answer to Goldsmith's question, by the way, is yes,[1] and discoveries along this line moved the project forward significantly. Parvizi's question about the meaning of "low pass filter" is not dumb either. It's a device that allows one to block electrical signals of low frequencies. Electrical signals are shaped like waves. A low pass filter blocks signals shaped like tidal waves while letting surface ripples slip through. But unless you are a high-octane electrical engineering student or a stereo equipment geek who obsesses about subwoofer settings, you have no good reason to know this. If you are either of these things, you probably can't remember when you didn't know the term's meaning. Goldsmith's widely used graduate-level textbook *Wireless Communications* frequently uses the term without ever defining it (2005, xvii, 3, 1045). This is not an oversight. It is Goldsmith's accurate estimation of the intended audience's vocabulary.

Because no one likes to feel dumb—academics least of all—it can be terribly tempting to limit our social and professional circles to those who already speak our lingo. But this would be truly dumb. If specialists sequester themselves among colleagues, we are all doomed. Anything worth doing is worth doing with a variety of specialists on board. Epilepsy, environmental problems, economic policies—progress on all these will stall if experts do only what has come to feel natural. But if more experts emulate Goldsmith and Parvizi in their willingness to feel like beginners again, long-standing problems might begin to disappear. Goldsmith put it this way: "When an interdisciplinary collaboration is in its infancy, it's hard to come together and work together on specific problems. But, I think that's where the interesting discoveries reside."

III. Foresight

Magic is about what's missing. Behold: The lovely assistant is sawed in half *without* any harm! Stand aghast: With *nothing* up his sleeve and *nothing* stowed in his top hat, he makes the white rabbit vanish! The advent of land-line based cordless phones awed us by their utter lack of curly cords, just as cell phones impressed us by being untethered to cords of any kind. The next great disappearing act in wireless communications is energy. My first cell phone—a fairly basic but rugged flip phone—needed to be recharged about every two days. A decade later, I own a smart phone that likewise needs to be recharged about every two days. What can be missed by focusing on this similarity is that in the past decade, the amount of energy-consuming tasks we ask our phones to perform has skyrocketed while the amount of energy they require to perform any given task has plummeted. Goldsmith anticipates that the energy requirements for cell phones and other wireless devices will eventually become a non-factor. Several years ago, CSoI sponsored a postdoctoral fellowship that allowed Goldsmith to collaborate with a rising star named Pulkit Grover on a series of projects related to "energy constrained communication." Goldsmith explains that cell phone producers have adopted the assumption that consumers prioritize high performance over battery life. Apple, Samsung, and their legion of competitors are assuming that most people share my willingness to recharge a phone frequently as long as it basically keeps up with the larger wireless world. Consequently, amazing new features will continue to debut on phones each year, their processors will continue to become dramatically more efficient, and we will all continue to keep our chargers handy.

But Goldsmith, never content to sit back and watch current trends unfold, wants to push the concept of energy constrained communications to the max. She wants to make recharging disappear. How? She explains:

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1 The slightly longer answer is that the epilepsy-inducing signals cannot be merely blocked by a filter; they must undergo a processing technique that keeps them from spreading throughout the brain. Goldsmith's initial idea, though, was right on track. Electronic devices could indeed succeed where drugs had failed.

> So, basically, you have to completely redesign the whole system from scratch with energy consumption minimization as your design constraint. And, one of the things I like about that problem, is that with everything about how we've designed systems up until now in wireless, you get to wipe the slate clean.

Given that Goldsmith knows consumers love high performance, why would she focus solely on reducing energy consumption? Because she is thinking way outside the cell-phone shaped box. She envisions wireless systems consisting of specialized devices designed to become permanent fixtures in their environment. She described miniaturized medical devices that can be implanted into a patient. If these devices can be made sufficiently energy efficient, they could be implanted once and then perpetually transmit medical data via a wireless network to wherever the data is most useful. Such devices could literally be lifesavers to the many people who have access to wireless devices but not to medical specialists. Goldsmith also mentioned devices which could be permanently implanted in highways or buildings, a step toward making them as smart as our smart phones.

This vision of the future will not materialize through researchers—not even the best of them—laboring in isolation. According to Goldmith, it will only happen through collaborations that truly set researchers free to be themselves even while working with researchers quite different from themselves. Such collaborations are advanced magic. Goldsmith has lead several large-scale collaborations that spanned multiple institutions. Of this type of leadership task, she sighs and says, "It's not easy." Goldsmith has been particularly impressed with the level of collaboration at CSoI. She credited them with "having the leadership and vision to make it work…somehow, they've created the magic to make it happen."

Luke Redington is a staff writer for CSoI.

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