DATA DELIVERY

RESEARCHERS TAP THE POTENTIAL OF MOBILE TECHNOLOGIES TO GATHER AND INTERPRET INFORMATION

|| BY DAYTON FANDRAY

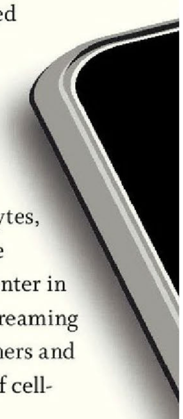
AS MARTIN LUKAC REMEMBERS IT, he never had a "Eureka!" moment. He describes it more as a slow transition.

As a doctoral student at UCLA's Center for Embedded Networked Sensing (CENS), Lukac was involved in efforts to use advanced sensor and communications technologies to increase our understanding of the physical world. Until 2005, this meant placing specially designed sensors or transducers in locations of interest—such as waterways, forests, highways and bridges—and gathering information that was then transmitted back to laboratories, where it could be analyzed by scientists or engineers. Researchers used this data to measure the levels of contaminants in the air or water, for example, or traffic patterns during rush hour, or the integrity of the structures under observation.

As effective as this approach was, it had drawbacks. The hardware could be expensive. And the objects of interest were not always in locations that had reliable Internet access for transmitting data. By 2005, however, CENS' director, Deborah Estrin, and her fellow researchers had begun to realize that a popular and increasingly pervasive consumer technology—the cellphone—had the potential to eliminate a great many of the challenges the researchers routinely faced.

"We were using these embedded devices with all of this custom hardware," Lukac recalls. "That was cool, because we could get the devices to do anything we wanted. But it takes a lot of effort to design and configure the hardware for each different application, and it ends up being expensive. As soon as people at CENS started using cellphones themselves, and realized there were already sensors built into the phones, we saw that we could start using them for things we traditionally used embedded hardware for."

The near ubiquity of cellphones is as important to researchers as the ever-evolving capabilities of the devices themselves, Lukac notes. Indeed, the most recent edition of the Cisco Visual Networking Index predicted that by the end of 2012, the number of "mobile-connected devices"—cellphones, smartphones, tablets, notebooks and so on—will exceed the number of people on the planet (more than 7 billion). By 2016, according to Cisco's estimate, there will be more than 10 billion mobile-connected devices, which will equal 1.4 mobile devices for every man, woman and child on the planet. Cisco predicts these devices will be working overtime, with mobile-data traffic around the world increasing 18-fold between 2011 and 2016 to a staggering 10.8 exabytes per month.



With 1 exabyte being the equivalent of 1 billion gigabytes, that adds up to a lot of information streaming around the globe. And John Shen, director of the Nokia Research Center in Palo Alto, California, believes a lot of that data will be streaming into the hands of people such as Martin Lukac—researchers and policy-makers who understand the incredible potential of cellphones and the networks that connect them.

Modern smartphones are equipped with an impressive array of sensors: There is the microphone and the now standard camera. But smartphones also come equipped with GPS technology that pinpoints the user's location geographically. Accelerometers detect movement—of both the device and the person holding it.

The touch screen uses a weak electric current to detect the motion of one's fingers. And, finally, there is the antenna, which can find a variety of signals ranging from Wi-Fi hot spots, to 3G and 4G cellular networks, to the presence of other mobile devices in the vicinity.

For casual users of smartphones, the built-in sensors are useful for taking pictures, talking to friends and keeping on-screen images properly oriented. The technology also gives service providers and third-party developers the ability to keep track of the users' movements, interests and activities. The sensors, in effect, are the basis of a mutually beneficial commercial relationship. Subscribers get goods and services they want, while service providers and app developers get the information they need to target the goods and services they are selling.

But the usefulness of cellular technology extends well beyond these commercial relationships.

"These sensors just crept in for practical, useful reasons," says Shen. "But once you had these sensors in a very portable device, researchers started looking at the devices and asking, 'Well, what can we do with them?'"

So far, researchers have answered that question by putting smartphones in the hands of willing volunteers in order to gather useful data on the environment, human and animal activity in the environment, and even the medical condition of the person carrying the device.

RECOGNIZING THIS LARGELY UNTAPPED POTENTIAL, Martin Lukac and his colleague Nithya Ramanathan decided to use cellular technology when a group of researchers at the University of California, San Diego, asked for their assistance in assessing the effectiveness of an initiative called Project Surya.

The project's goal is to improve health and environmental conditions in developing nations by replacing the cookstoves traditionally used in rural areas with a variety of clean-cooking technologies. Traditional methods of food preparation, explains Lukac, produce large amounts of black carbon in the form of soot and smoke. Breathing black carbon leads to acute lower respiratory infections and chronic obstructive pulmonary disease—Project Surya officials have estimated that, in

(CLOCKWISE FROM LEFT) COURTESY: MATTHEW MCKOWN, ABE BORKER, MARTIN LUKAC, MATTHEW MCKOWN

Above: In collaboration with Nexleaf Analytics, the Coastal Conservation Action Lab at UC Santa Cruz monitors seabird populations by using cellphone technology to transmit data collected by acoustic sensors. On Southeast Farallon Island (left to right), a solar panel charges a battery, which charges a smartphone; pigeon guillemots; Matthew McKown of UC Santa Cruz sets up a sensor; and Martin Lukac of Nexleaf Analytics deploys equipment.

India alone, there have been 400,000–550,000 premature deaths. And beyond the threat to public health, it is believed that black carbon is a major contributor to global climate change.

To determine the impact of this initiative, Lukac, Ramanathan and their colleagues at Project Surya used two crucial indicators: the amount of time villagers spent cooking on the new stoves, and an estimate of the black carbon concentration in homes where the traditional cookstoves had been replaced. Collecting this data in rural India and getting it back to the project managers in a timely manner might have represented a difficult, if not insurmountable, challenge a decade ago. But the proliferation of cellphones and supporting network technology—with coverage that now reaches even remote villages in India—enabled Lukac and Ramanathan to give their colleagues at Project Surya access to the data they needed.

The pilot phase of the project was launched in March 2009 in an Indian village in the northern state of Uttar Pradesh consisting of 485 households. The researchers designed a simple temperature sensor that plugs into the headset jack of a basic, programmable cellphone; this sensor allows Project Surya officials to monitor the temperature of the stove in order to track how long

COURTESY: ABHISHEK KAR

Left: Women in an Indian village use temperature sensors connected to cellphones, as well as air-sampling devices developed by Nexleaf Analytics, to collect data about stove use and black carbon levels. They email the data to scientists via smartphones.

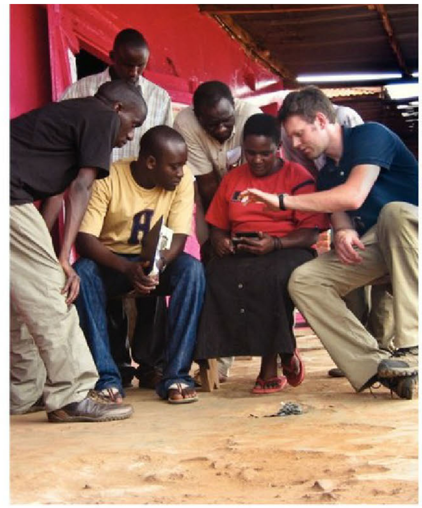
people were using the new cookstoves. To measure how this, in turn, affected the levels of black carbon in the home, the researchers developed a sampler device that pulls air through a quartz filter. As carbon is trapped by the filter, the filter darkens. All the participating villager has to do is remove the filter and, using the cellphone's camera, take a picture of the filter next to a carbon calibration chart developed by Lukac and his colleagues. The villager emails the picture, along with information about how long the filter was in the sampler, to the researchers' server. The server then analyzes the image and time frame to determine the carbon concentration for that household.

"Existing black carbon–concentration sensors cost anywhere from $6,000 to hundreds of thousands of dollars if you set up a whole lab, and they're bulky," Lukac explains. "We've done tests with the system we developed, and we wound up with results within 20 percent of the more expensive sensors. But altogether, ours cost maybe $600 to $700, so we're an order of magnitude cheaper and we're almost as accurate."

WHEN THEY STARTED WORKING with Project Surya in 2009, Lukac and Ramanathan founded their own nonprofit organization, Nexleaf Analytics. They are now using mobile-phone technology to facilitate research and economic development in a number of areas, such as their collaboration

COURTESY: GRAMEEN FOUNDATION

Esther Kibeti (left), a Community Knowledge Worker for the Grameen Foundation, helps farmers in Uganda's Kapchorwa District access real-time agricultural and weather information via a mobile phone. She has logged more than 1,000 farmer interactions in her two years in the role.



COURTESY: YAW ANOKWA

Carl Hartung (right)—a developer of the Open Data Kit, which the Grameen Foundation used to create apps for its project in Uganda—trains a Community Knowledge Worker.

with the Coastal Conservation Action Lab at the University of California, Santa Cruz.

The focus of this partnership is an effort to monitor seabird populations and evaluate the effectiveness of ongoing conservation efforts. Matthew McKown, a postdoctoral researcher at UCSC who is involved in the lab's work, explains that this is not a simple task using traditional research methods. The birds most at risk tend to breed on remote islands. Ideally, researchers would monitor populations by marking birds and recapturing them, but the logistics make this increasingly difficult and costly.

Fortunately, smartphone technology is giving the UCSC researchers a new way to keep track of seabird populations in remote locations, at a fraction of the cost associated with traditional tagging methods.

"Many of the most threatened species return to land only at night and nest in hidden locations, making them very difficult to monitor," McKown says. "The way these birds tip their hand is that they are quite social and vocal at colony sites. So the real clue to the presence of many species is their calling behavior."

Working with Nexleaf, McKown and his colleagues sought to exploit this behavioral cue by developing low-cost acoustic sensors that could be deployed in remote locations. Once in place, the sensors would capture the birdcalls and relay this data back to the mainland via smartphones and commercial cellular networks. The system is similar to the

COURTESY: KNOWME RESEARCH TEAM/ UNIVERSITY OF SOUTHERN CALIFORNIA

Research participants wear the KNOWME external sensor array under their clothing, and the medical data collected is then relayed to a smartphone via a Bluetooth connection.

Project Surya technology in that the acoustic sensors plug into the smartphone's headphone jack. Team members position the phones near probable nesting sites, and the phones essentially do the rest. They can be programmed to record data on a schedule that minimizes power consumption and, because they are "smart" phones, they can be reprogrammed on the fly, as conditions change. Ultimately, power is supplied by a solar collector that charges a lead-acid battery, which charges the phone's internal battery.

When the islands are close to shore—as in studies conducted in the San Francisco Bay area—data can be uploaded directly through an existing cellular network. When the islands are more remote, as in a study conducted on Southeast Farallon Island, CONTINUED ON PAGE 170

Puzzle on page 190.

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FROM PAGE 62 the smartphones record the birdcalls and upload the data to a local server via a Wi-Fi network that the team and its local collaborators—the U.S. Fish and Wildlife Service, PRBO Conservation Science and the California Academy of Sciences—have set up on the island. Once the data is gathered on the local server, it can be transmitted to the mainland via a microwave, satellite or other data link.

When McKown and his colleagues have the data in hand, they use computer-generated templates to isolate the birdcalls they are interested in. This allows them to determine mean calls per minute, a metric that appears to correlate well with the number of active nests on the ground.

"We went with the phones for a number of reasons," says McKown. "One, they're a mass-produced consumer product. That means they're power-efficient, user-friendly and pretty rugged. And we believe that, over time, the capabilities of the phones will continue to increase and the prices will go down. So we're getting better answers and reducing costs. It's amazing the flexibility that this offers us."

The trial run on Southeast Farallon Island ran for 80 continuous days without any need for human maintenance.

"The goal," McKown says, "is to have networks that will run in really remote locations for years, relying on only periodic—annual or biannual—maintenance."

THE OPEN DATA KIT REPRESENTS another approach to leveraging the flexibility and power of today's cellular technology. The kit is actually a suite of open-source software tools developed by a team of computer scientists—led by Gaetano Borriello, professor of computer science and engineering, and including doctoral students Yaw Anokwa and Carl Hartung—at the University of Washington. With Open Data Kit (ODK), organizations can design and build their own smartphone applications, thereby reducing the cost of any project that involves gathering data, especially in developing regions.

"We have done a lot of work on health care in developing regions," explains Anokwa. "And the common theme we saw was that when you collect data on paper, you make mistakes. It's hard to transport the data, it's hard to search, and by the time you have entered the data, it has been months since you collected the data. So it's hard to take actions based on it."

Smartphones increase accuracy and eliminate the time lag. They also give people in the field the ability to collect richer data.

"You can add GPS coordinates to the data-collection session," he says. "And if you're a doctor dealing with a rash, you can take an image of that rash. You can record the sound of a cough. You can put all of that stuff into the record. And given the direction smartphones are going, it seems likely that eventually we'll be able to attach sensors to those phones to gather even more interesting environmental data or patient diagnostics."

ODK's first field test was conducted in Uganda, when the Washington, D.C.–based Grameen Foundation used the kit to create two smartphone apps: one to collect geo-tagged data from farmers and another to give those farmers timely access to expert agricultural information. Local intermediaries, selected by their communities, were given smartphones. When villagers had questions or concerns, they could approach these Community Knowledge Workers, or CKWs. Using the smartphones, the CKWs could then access an agricultural database and get relevant answers.

"Agricultural extension services have been provided around the world for many years," explains Heather Thorne, vice president of information services for the Grameen Foundation. "But the challenge in Africa is that those organizations are understaffed. We started to see that mobile-phone penetration was increasing dramatically in Africa—Uganda alone has almost 100 percent network coverage. So we started thinking about the model of providing intermediaries with phones. We felt we could really start to close that information gap to those farmers."

Connected by mobile technology, village-level intermediaries eliminate the need to field a virtual army of extension agents—a costly and slow process. When crops are dying, for example, farmers don't really have time to wait for assistance to arrive overland. The cellular connection also allows Grameen to reach the poorest people, who tend to live in the hardest-to-reach locations.

Thorne notes that this system is not only capable of delivering information to villages on a timely basis, it also gives the foundation the ability to continuously monitor the effectiveness of the services it provides and determine areas where more resources should be directed. In some villages, for example, nutritional information might be a priority. In others, it could be information about alternative crops that are more resistant to flood or drought. With data going back and forth constantly, it is easy for Grameen to fine-tune the information provided to each community.

This approach has yielded tangible results. Thorne cites the example of an effort to contain an outbreak of blight that was wiping out the banana crop in two of Uganda's agricultural districts. Partnering with the International Institute of Tropical Agriculture, the foundation's representatives used their smartphones' GPS positioning capabilities to pinpoint plots where the disease had taken hold. The representatives then questioned the farmers to determine what they knew about containing the disease and preventing its spread to other plots. The interviews revealed that the farmers knew part of the answer. They were cutting off the diseased buds and burying them, which is the first step in controlling the spread of the blight. But they weren't sterilizing the blades of their machetes afterward. Thus, the disease was spread from plant to plant via the infected machete blades. Having identified the problem, Grameen's CKWs instructed the farmers to sterilize the blades in a fire after cutting off infected buds.

"It was a simple information campaign, demonstrating what to do and what not to do," says Thorne. "We then went back out and resurveyed, and found that there was a significant increase in the level of knowledge and a change in behavior that

WE LIVE IN AN AGE OF UBIQUITOUS COMPUTING. GETTING "OFF THE GRID" IS NOT REALLY A VIABLE OPTION FOR MOST OF US. THE GRID IS WHERE MODERN LIFE HAPPENS.

affected the spread of the disease, which we were able to map over time."

Working in developing nations presents challenges, however. And many of these relate to cultural and environmental conditions that cannot necessarily be anticipated in the research lab.

"The first time we took the application out into the field in Uganda, I built what I thought was this elegant, beautiful user interface," recalls Anokwa, an ODK developer. "But when the farmers touched the screen, it wouldn't work. I would touch the screen, and it would work. So we got to looking at the farmers' fingers, which had developed calluses from fieldwork. Programmers don't have calluses. So we had to tweak the user interface [by making the touch-screen buttons larger] to make sure it supports those kinds of users. Field experience gives you a sense of the user and a sense of the organization you're trying to serve."

WHILE CELLULAR DEVICES ARE FINDING their way into both scientific research and economic development abroad, a number of researchers are exploring their potential for improving health and reducing the cost of delivering quality health care worldwide.

At the University of Southern California, a team of researchers, including Murali Annavaram, is working on a project that is capable of streaming real-time data on metabolic health directly from at-risk patients to medical facilities where it can be monitored by health-care professionals. Dubbed the KNOWME Network, the system consists of an external sensor array that is worn under the patient's clothing. The sensors keep track of the patient's heart rate, blood-oxygen levels and levels of physical activity. This data—gathered at the rate of 300 samples per second—is then relayed to the patient's smartphone through a wireless Bluetooth connection. The phone takes the information, adds data of its own (such as GPS location), and sends it to central file servers where it can be analyzed.

The team's current focus is teenage obesity. By combining data from a number of sensors, the system can make a precise determination of a patient's activity levels throughout the day. And according to Annavaram, who holds the Robert G. and Mary G. Lane Early Career Chair at USC's Viterbi School of Engineering, the system also could be adapted to monitor other medical conditions.

"We can detect whether you are walking or watching TV," he says. "We can detect subtle differences in the physical state of the person who is wearing the sensor suite—such as whether he or she is just sitting, or sitting *and* fidgeting—by combining the accelerometer information with electrocardiogram sensing information."

The data can be gathered around the clock, wherever the research participant is, eliminating the need for frequent hospital visits. And, Annavaram notes, KNOWME not only keeps clinicians informed about the patient's condition, it provides feedback directly to the patient. After three hours of inactivity, the screen on the phone goes red, encouraging the participant to get moving.

Annavaram, like most researchers who are working with smartphones, says that one of the biggest challenges his team has faced is finding a way to maximize battery life. "It's a very precious resource. And these phones were not designed to do non-stop, continuous monitoring of this nature. When you collect 300 samples and do analysis on them every second, it's a fairly heavy load on the device."

The answer, for Annavaram and others, has been an attempt to collect data intelligently. This means identifying which pieces of information can be safely ignored and eliminating them from the data stream. It also means sampling less frequently when the data is expected to be consistent over a long period of time—such as when a teenage participant is sitting in class or when seabirds are known to be sleeping. Since smartphones are essentially pocket-size computers, it is fairly straightforward to program them accordingly.

Another challenge identified by the KNOWME team, as well as many researchers, is the human factor. The teens recruited to participate in the KNOWME Network were reluctant to carry the Nokia N95 phones originally distributed for the study. They complained that the phones were too thick and wouldn't fit in their pockets. When the researchers gave them thinner Nokia E75 models, the teens happily agreed to carry them. Similarly, Yaw Anokwa and his team thought they had designed an elegant user interface for their work in Uganda, but ran up against the unanticipated challenge of callused fingers.

PRIVACY IS ANOTHER VITAL CONCERN that must be addressed as sensor networks proliferate and become ever more sophisticated. Studying the mating habits of seabirds is one thing—monitoring a teenager's location and vital signs is quite another.

The teens who are participating in the KNOWME study are volunteers, so they have agreed to have their activities monitored. But protecting that data and maintaining doctor-participant confidentiality is an obligation that Annavaram and his colleagues take seriously.

"How do you make sure the data is secure?" Annavaram asks. "How do you make sure it is preserved in a way that only the right person can read the data? There are many issues we still have to solve."

Despite the challenges that remain, we live now in an age of ubiquitous computing. Getting "off the grid" is not really a viable option for most of us. The grid is where modern life happens.

That a compact, mobile computer—designed and marketed primarily as a piece of consumer electronics—can also be used to monitor levels of air pollution in remote Indian villages and the exercise habits of teen participants in Los Angeles is one of those happy accidents that sometimes change the way we look at the world around us. And with all of those sensors out there, constantly on the move, it seems safe to say that everything will soon be coming into sharper focus. ▲

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