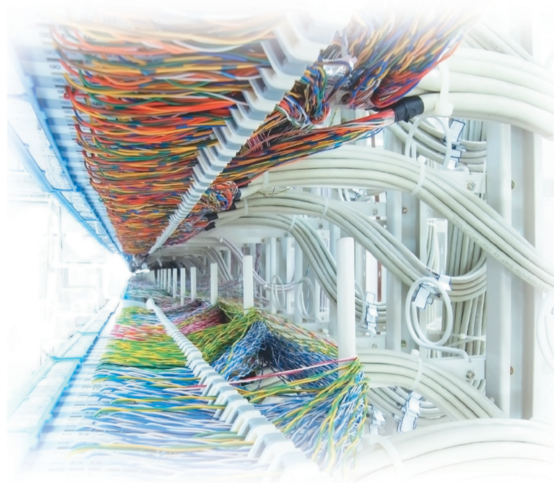
# Mobile Security: Finally a Serious Problem?



Neal Leavitt

**The growing popularity of wireless technology may have finally attracted enough hackers to make the potential for serious security threats a reality.**

In the world of computers and communications, the more widely a technology is used, the more likely it is to become the target of hackers.

Such is the case with mobile technology, particularly smartphones, which have exploded in popularity in recent years. According to market analysis firm ABI Research, 370 million smartphones were in use globally last year.

Many users download mobile applications with little regard to whether they're secure, providing a ready way for hackers to attack the devices.

In addition, said Gustavo de Los Reyes, executive director for AT&T Security R&D, "These phones are being used frequently for sensitive transactions like banking, mobile payments, and transmitting confidential business data, making them attractive targets if not protected."

"The payoffs—financial and personal information—could be huge," noted Purdue University computer science professor Richard P. Mislan.

Smartphones generally connect to the Internet, as well to PCs for software updates or media synchronization, providing convenient attack vectors.

Device makers and wireless-service providers have long focused on communications and other services, with security remaining an afterthought.

Referring to the two most popular smartphone platforms, Ed Moyle, senior analyst with market research firm Security Curve, said, "Security is now playing catch-up with the rapid adoption of Android and iPhone, both of which are hard for enterprises to manage."

Thus, after years of warnings about mobile security, there finally appears to be a reason to worry.

In fact, the number and types of mobile threats—including viruses, spyware, malicious downloadable applications, phishing, and spam—have spiked in recent months.

For instance, McAfee Labs' threat report for 2010's fourth quarter reported a 46 percent increase in malware targeting mobile phones over the same time period the previous year.

"We're seeing more than 55,000 new pieces of [mobile] malware on a daily basis," said Dave Marcus, McAfee Labs' director of security research and communications.

## THREATS ON THE MOVE

Mobile devices increasingly face various types of threats, as Figure 1 shows.

### Botnets

Attackers form a botnet by infecting multiple machines with malware that victims generally acquire via e-mail attachments or from compromised applications or websites. The malware gives hackers remote control of the "zombie" devices, which can then be instructed to perform harmful acts in concert.

"These command channels could also provide a way to update the malicious code so that it will communicate or act differently," said Juniper Networks research engineer Troy Vennon.

The easiest way for an attacker to benefit from a mobile zombie network is to send SMS or multimedia message service (MMS) communications to a premium phone account that charges victims fees per message, explained Vennon.

The scammers act as the premium-account owner's affiliates, receiving some of the money that their attacks generate, noted Bradley Antsis, vice

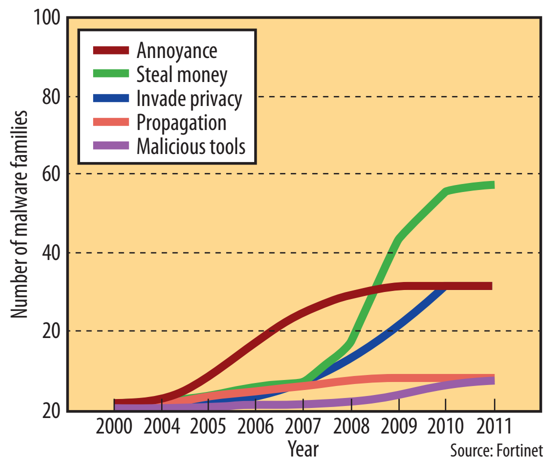



**Figure 1. The number of threats to mobile devices, particularly those designed to steal money, has increased steadily during the past few years.**

president of technical strategy for security vendor M86.

The Yxe malware family that hit China last year caused this problem.

Also in 2010, malware originating in Holland exploited a vulnerability in jailbroken smartphones—those that owners have modified to gain OS root access and remove manufacturers' usage limitations—to create a botnet. The network sent SMS messages to premium numbers.

Last year, another mobile botnet targeted European customers of a Dutch online bank. The malware used in the attack included command logic that gave the hacker remote control of victims' smartphones.

With PCs, hackers often use zombies within botnets to launch denial-of-service attacks. Thus far, though, there have been no major mobile DoS incidents.

## Malicious applications

In some cases, hackers have uploaded malicious programs or games to third-party smartphone-application marketplaces—such as those for Apple's iPhone and Google's Android devices—or have otherwise made them available on the Internet.

"These malicious apps are usually free and get on a phone because users voluntarily install them," said Pierluigi Stella, chief technology officer for Internet security vendor Network Box USA.

Once on a handset, the programs steal personal information such as account passwords and logins and send it back to the hacker. They also open backdoor communication channels, install additional applications, and cause other problems.

Most mobile application marketplaces don't require that code in applications be cryptographically signed by the developer before it can be uploaded, noted Kurt Stammberger, vice president of market development for security vendor Mocana.

"Until this becomes common," he said, "malicious apps will proliferate quickly on mobile platforms."

## Social networking

As smartphone use has grown, so has mobile social networking.

Malicious links on social networks can effectively spread malware. Participants tend to trust such networks and are thus willing to click on links that are on "friends'" social networking sites, even though—unknown to the victim—a hacker may have placed them there, said M86's Antsis.

Clicking on a link could download a malicious application on a victim's computer, said Network Box USA's Stella. This could let a hacker place Trojans, spyware, and backdoors on the machine and even conduct identity or information theft, he added.

Some schemes use a sensational headline or promise information on a current hot topic to grab readers' attention and encourage them to click on a malicious link.

## Spyware

Hackers can use spyware available online to hijack a phone, allowing them to hear calls, see text messages and e-mails, and even track a user's location through GPS updates.

Most commercial mobile spyware applications send an update of captured communications or location data to a website where the spy logs in to view the data, noted Juniper Networks' Vennon. In some cases, SMS communications inform the spy that the system has obtained new data.

The software can even create a hidden access point inside a mobile phone that lets a hacker turn on the device without it ringing, in essence converting it into a microphone, said Purdue University's Mislan. The spy could then hear nearby conversations.

While some malware writers sell or give away mobile spyware, there are also online vendors—such as ClubMZ, FlexiSPY, and Retina-X Studios—that sell the software commercially.

These companies say their products are only for legal uses and can be helpful in finding a stolen mobile device or in monitoring the activities of children, as well as employees using company phones.

Mobile phone spyware is illegal in the US but is sold by websites hosted elsewhere, noted Simon Heron, principal with Network Box's UK office.

## Bluetooth

Bluetooth enables direct communication, including the sharing of content, between mobile devices.

Wireless devices can broadcast their presence and allow unsolicited connections and even the transmission of executables if users don't configure their Bluetooth operations appropriately.

On rare occasions, mobile malware—such as the Cabir worm—has used Bluetooth to propagate.

## Wi-Fi

Hackers can intercept communications between smartphones and Wi-Fi hotspots.

The fundamental vulnerability is hotspot architecture with no encryption to protect transmitted data.

"If a user connects to [such] a hotspot for the first time, the end-to-end connection between the user's device and the hotspot provider is not secured, so the [hacker] can intercept and control the user's traffic," said Carnegie Mellon University computer science professor Patrick Tague. In this scenario, the hacker gets between the user and the hotspot provider and hijacks the session via a man-in-the-middle attack.

A hacker can also set up a peer-to-peer network that mimics a Wi-Fi hotspot offering a high-quality connection, which entices users to connect. The hacker then intercepts victims' transmissions without their knowledge.

## Phishing

Phishing poses the same risk on smartphones as it does on desktop platforms.

In fact, many users trust their mobile device more than their computers and thus are more vulnerable to phishing.

Additionally, said Juniper Networks' Vennon, the lack of maturity in phishing filters and reputation-based services in mobile browsers, combined with the immediacy and portability of telephone communications, makes the platform attractive for phishers.

Mobile phishing is particularly tempting because wireless communications enable phishing not only via e-mail, as is the case with PCs, but also via SMS and MMS, noted AT&T's de Los Reyes.

Social media phishing is becoming a major issue as social networking sites contain an increasing amount of personal information that phishers can use to make their attacks more effective, said Paul Henry, security and forensics analyst for market research firm Lumension Security.

**The number and types of mobile threats—including viruses, spyware, malicious downloadable applications, phishing, and spam—have increased in recent years.**

## TRADITIONAL SECURITY APPROACHES

Mobile communications can use the same types of security—including antivirus and firewall products—as fixed communications. Vendors include Fortinet, F-Secure, Juniper Networks, Kaspersky Lab, Lookout Inc., Mocana, NetQin, Trend Micro, and Trusteer.

Most of these products work much like their PC counterparts. For example, mobile antivirus products scan files and compare them against a database of known mobile malware code signatures. Noted Mocana's Stammberger, this approach is compute-intensive and "eats batteries for lunch."

Mobile security software is also more likely to use the cloud to offload some of the processing typically associated with PC-based products, said Chris Perret, CEO of security vendor Nukona.

There are only a few mobile encryption software products, including SecurStar's Phonecrypt and Credant Technologies' Mobile Guardian for Handhelds. They're scarce primarily because they're challenging and expensive to develop.

"Restricted [OS] kernel access means you can't put the cryptographic processes sufficiently low down in the stack, close to the silicon. Processor limitations, memory constraints, and battery-life issues make some of these apps as slow as molasses," explained Stammberger.

## OTHER MEASURES

Security vendor MobileIron recently launched a storefront so that businesses can deliver mobile applications directly to employees without posting them publicly. This lets businesses enforce security policies about which users and devices can access specific corporate applications.

This summer, trials will start for the AT&T Smart Mobile Computing platform, which will include features such as mobile security, mobile device management, a virtual private gateway, encryption, policy controls, a virtual desktop, and cloud computing capabilities. Customers will also be able to apply their own security policies to this platform.

The AT&T Security Research Center recently opened in New York City. Employees have expertise in a broad range of areas, including security, cellular systems, networking, and data mining.

Under a distribution and marketing agreement signed last year, Verizon Wireless will promote Lookout Inc.'s mobile security products to customers.

Handset and chip makers are also addressing mobile threats. For example, Mocana's Stammberger said his company is working with Freescale Semiconductor, IBM, Intel, LG, Motorola, and Nokia to "better leverage and improve their on-chip crypto-acceleration hardware."

Mocana also sells Acceleration Harness, a technology for connecting OS-based security software with on-chip hardware acceleration.

As the mobile ecosystem evolves and hackers probe for vulnerabilities, devices will face a growing number of the types of attacks traditionally launched against desktop systems, said Trusteer chief technology officer Amit Klein.

"We need to implement mobile security solutions now to protect against these new threats," he added.

"The greater visibility of these attacks will place an increasing importance on mobile device makers having enterprise-grade security features and configuration options in place. It will become necessary for security to be considered in all phases of application development to ensure that resiliency against attacks is built into mobile devices from the start," said Adrian Stone, director of security response for BlackBerry vendor Research in Motion.

"Our dependence on an always-on, connected, mobile device environment is going to be profound in critical contexts that we can't imagine today," said Stammberger. "We have to be able to trust these devices, but we can't now. There's still a lot of work that needs to be done to get to the point where that trust is warranted."

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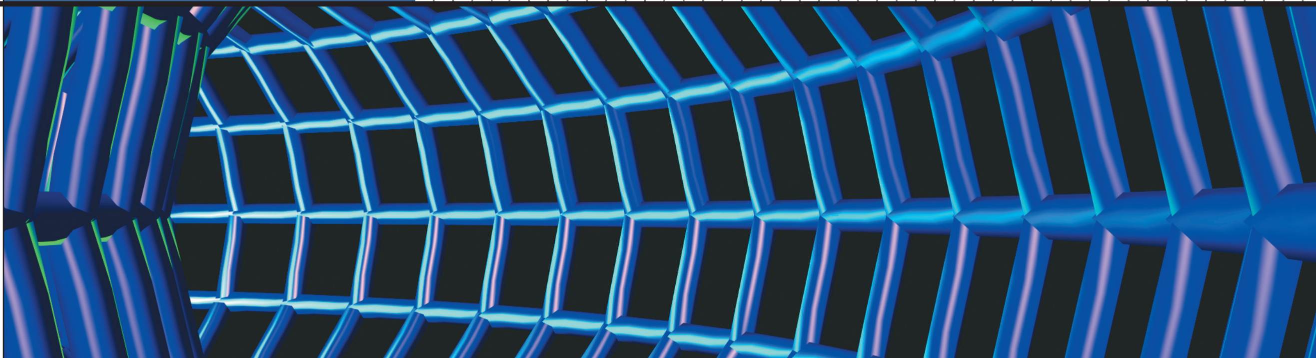

# Understanding and Using Rendezvous to Enhance Mobile Crowdsourcing Applications

**R.J. Honicky,** *Nokia Research Center, Berkeley*

**Researchers are exploring the rendezvous concept—bringing sensors close to one another in space or time—as a way to make sense of disparate data collected by individuals. Applications such as participatory atmospheric sensing illustrate the potential of rendezvous to help create powerful mobile applications.**

As mobile phones increasingly become general-purpose devices, phone manufacturers have integrated various sensors into them. For example, even low-end phones now include cameras, and mid-range phones often include GPS capability for use with popular mapping applications. Accelerometers and magnetometers provide a level of immersion and integration between the virtual and physical worlds that enable next-generation augmented-reality applications, such as Wikitude, Star Walk, Dish Pointer, Work Snug, and Car Finder. The "Categories of Mobile Sensing Applications" sidebar defines a proposed classification for mobile sensing applications.

At the same time, crowdsourced information—such as Wikipedia and online reviews—now dominates the Internet. Distributed processing projects such as SETI@home and Folding@home illustrate the power of distributed processing and illuminate people's willingness to contribute their own idle resources toward social and scientific advancement. Applications such as cell tower location databases, traffic flow monitoring, and pothole detection have the added characteristic of automatically integrating sensor data from mobile devices.

Bringing these two trends together with *rendezvous*—when two or more sensors come close to one another in space or time—offers the potential for powerful new applications that exploit these characteristics.

## MODELING RENDEZVOUS

People rendezvous quite frequently, but only in the past few years has the ubiquity of mobile phones, particularly those with GPS technology, enabled applying the concept to the large-scale study of human mobility. Although GPS receivers have long been available, coupling them with mobile phones has drastically simplified the data collection and storage process, putting studies with hundreds of users over years within reach of researchers with modest budgets. These studies continue to shed light on the nature


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of human mobility, and most importantly, rendezvous. For example, mobile-phone calling records have recently revealed Lévy walk mobility patterns in human mobility,[1] making it possible to better model and understand mobile systems.

A study by Kyunghan Lee et al.[2] described an algorithm based on the principle of least action. According to this principle, people plan their trips so that they visit nearby destinations at around the same time. These investigators describe how this algorithm not only corresponds well to real human mobility patterns, but also has important consequences for the frequency and distribution of rendezvous between users. This work provides an important tool for evaluating rendezvous-based algorithms.

Much delay-tolerant networking (DTN) literature builds on assumptions about rendezvous, which provides opportunities for mobile devices to exchange data when they are within communication range. The accuracy of mobility models[2] and social relationship models[3] has a significant impact on routing-algorithm design and performance. The DTN literature thus offers significant analysis and insights into human mobility and rendezvous.

The most mature and well-studied application of rendezvous in the DTN literature is opportunistic, peer-to-peer routing (sneaker nets), in which data passes between mobile devices with the goal of eventually reaching a destination.[4] Each rendezvous represents an opportunity for mobile devices to exchange data. These data exchanges might take place either among unrelated devices or within a federated set. Rendezvous among a user's laptop, phone, and set-top box, for example, might provide opportunities for data transfer over low-power, high-bandwidth connections.

DTN-based routing, however, is only one of several potential applications. In most cases, rendezvous is also essential to data fusion. In the physical world, proximity in space and time often corresponds to a high correlation and systematic relationship among sensor readings. Understanding the relationships among sensor readings from nearby sources can enable us to combine the readings, increasing the quality and quantity of data available in the system.

For example, consider atmospheric sensing for pollution monitoring. If two sensors are close to each other, they should read almost the same values. If they do not, at least one is miscalibrated. The closer the sensors are, the more closely they should agree. Thus, rendezvous between sensors can help determine the relative miscalibration among sensors. Knowing the true calibration of some sensors in the system, or the statistical distribution of miscalibrations, makes it possible to determine the sensors' absolute calibration. Well-calibrated sensors can significantly increase the system's accuracy. Both the CaliBree system from the MetroSense project at Dartmouth,[5] and research efforts at Berkeley, Intel, and Nokia demonstrate this capability.

## CATEGORIES OF MOBILE-SENSING APPLICATIONS

**A useful way to look at mobile-sensing applications classifies them in terms of four levels of integration of the data from different users.**

- ***Personal sensing*** **applications typically serve only the needs of one user and do not require interaction with other devices. An application that records notes, lectures, or concerts for an individual's later use is one simple example.**
- ***Shared sensing*** **takes such applications one step further by permitting easy data sharing. For example, a shared-sensing application could record a concert and then automatically post, stream, or send it to someone else via messaging.**
- ***Contextualized sensing*** **applications automatically augment sensor data using other information. In the concert example, that data might be the recording device's location and orientation.**
- ***Sensor fusion*** **applications use contextual data to combine measurements from different, possibly heterogeneous, sensors together. Such applications could, for example, improve an audio recording's quality by automatically combining it with other recordings, based on location data.**

**Today, many mobile-sensing applications fall into the personal, shared, or contextualized categories. When people converge in space or time, however, opportunities arise to truly make the data's value greater than the sum of its parts. Developers and researchers can use this convergence—also referred to as rendezvous—to enhance mobile applications and experiments, increasing the value of collected information.**

In sensing systems, precision roughly corresponds to the number of bits of (meaningful) information a sensor provides; accuracy corresponds with the correctness of those bits. Calibrated sensors let systems take advantage of rendezvous to increase precision by averaging readings from sensors located close to one another.[6,7]

When a system wants to sense a quantity for which a phone does not have an appropriate sensor, it can "borrow" sensors from nearby phones. Shane Eisenman et al. discussed secure mechanisms for letting users borrow sensors from appropriate nearby devices.[8]

These examples describe powerful ways in which researchers have already exploited rendezvous to intelligently combine information from different sensors. These are first steps in understanding how to take advantage of rendezvous to build more situated, immersed, and representative computer systems.

Readers interested in a more in-depth mathematical understanding of mobility should examine a study by Marta Gonzalez et al. in which they used mobile-phone records to analyze human mobility,[1] the SLAW algorithm described by Kyunghan Lee et al.,[2] and a social-based forwarding algorithm investigation conducted by Pan Hui et al.[3] in which they used several different rendezvous datasets.

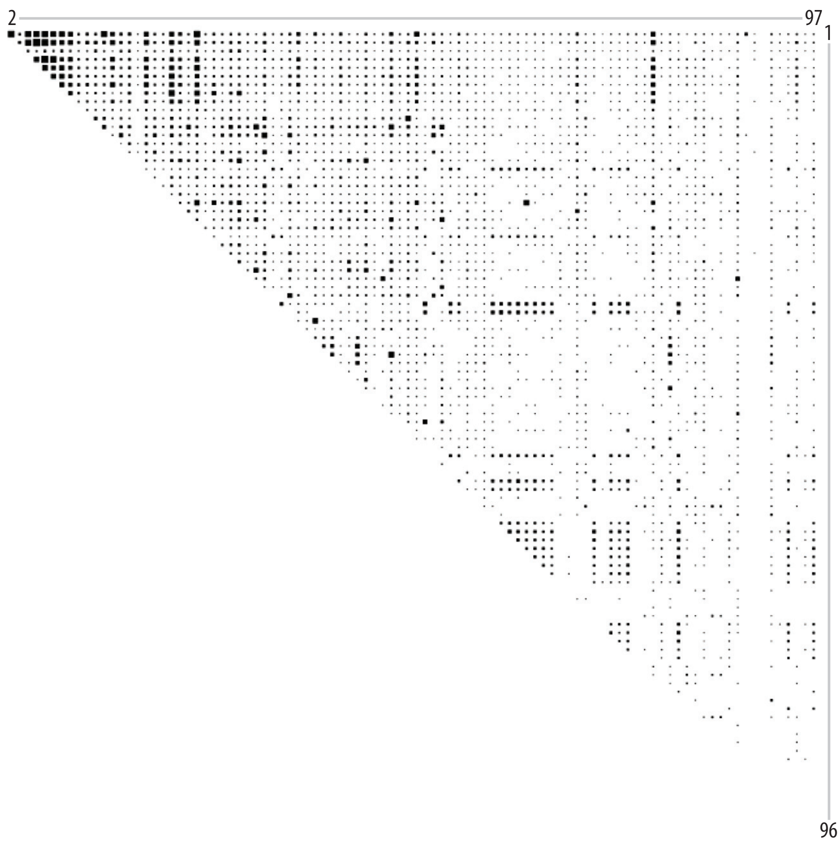


**Figure 1.** Each square represents the number of times a user rendezvoused with another user in the study, ordered by the total number of rendezvous for a given user. Surprisingly, most users interacted at least slightly with most other users, although some users in this cohort clearly interact more frequently with others. Only 466 user pairs (about 11 percent) did not interact with each other at all; several such pairs contain users who did not participate in the study for very long.

## QUANTIFYING RENDEZVOUS: REALITY MINING

The widely available dataset from the Reality Mining project offers a concrete picture of how often and where people rendezvous.[7] This project used software on mobile phones to track user behaviors over the course of approximately nine months from 2004 to 2005. Among the 100 study participants, 75 were students or faculty at the MIT Media Lab, and 25 were incoming students at the MIT Sloan School of Management. The software collected statistics on incoming and outgoing communication, as well as the Bluetooth and GSM beacons detected by the phone.[9] The results exclude data from three of the 100 users because they did not participate significantly in the study. The study's large scope had a significant impact on our quantitative understanding of social interaction.

Because of a Bluetooth beacon's limited range, the Reality Mining data indicates when participants were close to one another. Since these users worked nearby, they provided a mechanism for studying the effects of increasing user density in a small area.

Note that the participant selection process for the Reality Mining study is unclear and almost certainly biases the data. However, the objective was to gather data in an area where a reasonable percentage of people use a system that leverages rendezvous. Therefore, a dataset that selects 100 users randomly from, say, all of Boston, would be far too sparse to simulate a high penetration rate for a rendezvousing application.

The MIT Media Lab consists of 300 to 400 people, and the Sloan School of Management, 1,000 people. Thus the Reality Mining data's gross density of users in these two groups is 20 to 25 percent and 2 to 3 percent, respectively. Obviously, biases in the selection process might cause the results to skew toward a much higher penetration, but that is not problematic for these results because the goal was to understand macroscopic rendezvous characteristics and how they might apply in a situation in which a mobile application has high penetration.

In Figure 1, each square represents the number of times a user rendezvoused with another user in the study, ordered by the total number of times a given user rendezvoused. Although some users in this cohort clearly interacted more frequently with others, most users interacted at least slightly with most other users. The most connected user rendezvoused 6,256 times during the study, and the most connected pair of users rendezvoused 585 times. The median number of rendezvous was 862, and the median number of rendezvous between two users was one.

This data suggests that most users rendezvous quite frequently. It also raises the question of how many people congregate at one time, and for how long people rendezvous. For each user in the study, Figure 2 shows the number of other nearby users versus time. The maximum number of nearby users was 15. Interestingly, many users frequently congregated with other users.

Figure 3 shows the time that a user is in proximity to a given number of other participants, ranked by fraction of time in proximity to at least one other participant. The 5th, 50th, and 95th percentile users were at 0.0039, 0.052, and 0.16. That is, the median user spent about 5.2 percent of the recorded study time in proximity to at least one other user in the study. This figure shows that, in fact, many participants spent a significant amount of time close to other participants, and even the least-connected participants rendezvoused occasionally.

This data does not, however, immediately reveal where it's possible to increase precision. Instead, it's necessary to consider GPS locations.

## PARTICIPATORY ATMOSPHERIC SENSING

Consider an application that can benefit from detecting and exploiting rendezvous between users: *participatory atmospheric sensing*. Rendezvous provides opportunities for automatic sensor calibration, and for increasing system precision. Furthermore, personal mobile sensors will sample the most in areas of high user density, so for atmospheric compounds that affect people, the sampling density will, in some sense, approximate an ideal sampling distribution.

Participatory sensing has other important benefits. For example, since the sensors move with people, they track individual exposure. In our study conducted in Accra, Ghana, West Africa,[10] several users changed their daily routes and habits as a result of carrying pollution sensor hardware. Some users expressed concern and outrage over the pollution levels in their communities and sought ways to actively reduce pollution.

Whether motivated by the desire for social change, scientific inquiry, or personal interests, researchers have paid

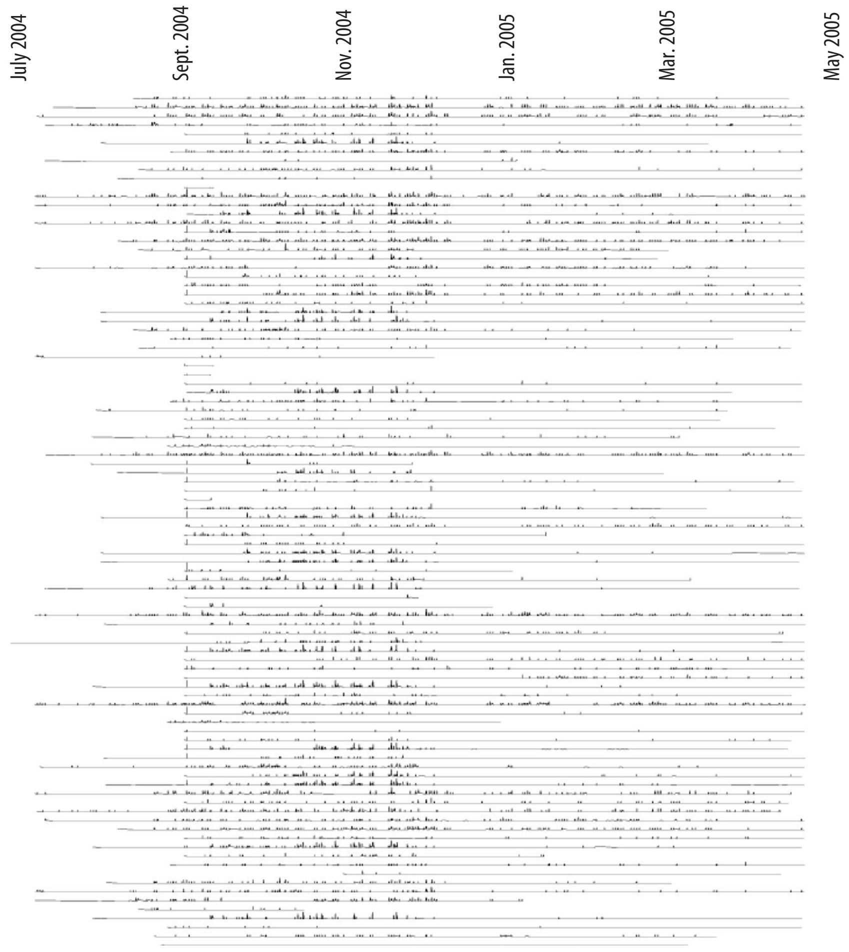


**Figure 2.** Each line shows the number of users in proximity to a given user, for each user in the study. The height of each line represents between 0 and 15 users in simultaneous rendezvous. Many users frequently congregated with several other users.

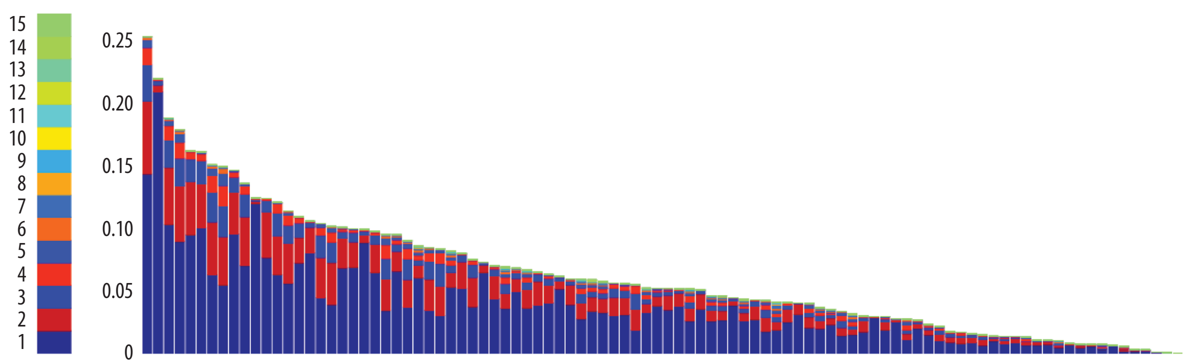


**Figure 3.** Fraction of time that a given user is in proximity to other participants, ranked by fraction of time in proximity to at least one other participant.

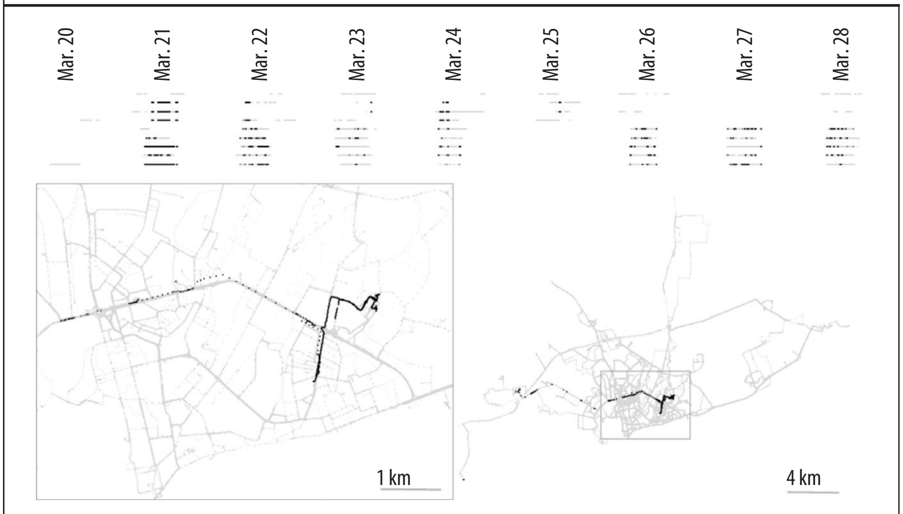


**Figure 4.** Rendezvous points (black) superimposed on all locations (gray) in the Ghana study. Sample times for each sensor appear at the top, again with rendezvous points in black and all sample times in gray. This figure shows that rendezvous occurred in hotspot locations, rather than being distributed throughout the map. They are not isolated to a few lucky coincidences, but distributed throughout the study in time and location.

increasing attention to the potential for individuals and scientists to harness information gathered by members of society.[6] For example, Jason Corburn examined the larger idea of *citizen science*, in which community members take part in the observation or analysis of their environment or in other scientific studies.[11] Corburn also discussed *street science*, in which participants use data to effect social change.

Our Common Sense project (www.communitysensing.org) has performed three major sensor deployments since 2007. Besides Ghana, the project has also deployed sensors on street sweepers in San Francisco[12] and badge devices carried by community activists in West Oakland.[13] These badges transmit sensor and location data into a database, but they do not contain voice equipment. Because the Ghana and West Oakland studies included user location information, they provided a resource for examining real-world user rendezvous.

The study in Ghana consisted of 10 users, one of whom left the study early due to equipment failure. Six users were taxi drivers, and four were university students. The taxi drivers ensured good geographic coverage, although their movement is not necessarily representative of typical people. As with the Reality Mining participants, these users came from a geographically dense subset of the population, and thus very roughly simulated an application having high user penetration. Shanghai Jiao Tong University recently completed a more extensive data collection campaign focused on taxi mobility (http://wirelesslab.sjtu.edu.cn).

Figure 4 shows the location histories of nine participants in the Ghana study, along with a timeline of samples. Again, the selection process for participants was heavily biased toward a small geographic area. The gray dots represent sample locations, and the black dots represent rendezvous between users. The users rendezvoused throughout the study's geographic area, although they tended to rendezvous in specific hot spots.

Figure 5 shows a similar plot for the West Oakland study. Again, users rendezvoused throughout the study period, supporting the intuition that rendezvous is a frequent occurrence rather than a lucky coincidence or abnormal event. The stars represent GPS error, which typically occurred when the devices were indoors, so they actually reduce the probability of rendezvous, because if users are in the same location, they have a lower chance of rendezvous in the event of a GPS error. The location data from this study is extremely biased because some participants spent significant time together, making the data valuable for calibrating sensors, rather than for illustrating typical rendezvous behavior.

Nonetheless, at a macroscopic level, these results are consistent with the findings of Lee et al., who analyzed approximately 150 GPS traces from 66 users in five separate locations and found that people moved among clusters of locations.[2]

Real-world location and sensor data provided a basis for automatically calibrating sensors in the Oakland study. Figure 6 shows the raw analog-to-digital converter data, smoothed ADC data, and the data after automatic calibration.[6,7] Since there is no absolute reference sensor in the data, the $y$-axis scale is unlabeled. We only know the relative calibration unless one of the sensors has absolute calibration information. If we had either the true calibration of one of the sensors, or knew the distribution of sensor miscalibrations, we could infer the absolute calibration of each sensor.

Although study participants moved independently, they spent the most time in the same general area. Thus, the smoothed sensor signals, which roughly correspond to the ambient pollution concentration, should match. Figure 6 shows that this is indeed the case after calibration.

As the immersion of sensors and communication into daily life continues, applications will emerge that can combine data that individuals acquire with data from other sources. These important applications will help make sense of oceans of noisy data.

Mapping applications that contextualize user data have taken a first step in this direction, but leave data fusion for users to perform. Other potential applications in this area might include an audio capture and enhancement application, indoor localization through time-of-flight calculation of sound events recorded by different devices, and forming ad hoc phase array antennas for higher-gain GPS signal reception. Privacy and energy are important issues that warrant separate treatment.[14,15]

Of course, economics will dictate what sensors make their way into phones and other mobile devices. Although altruism might suffice to spur the development of such applications, the objective is to find a compelling economic model for collaborative sensing applications in general, and for mobile atmospheric sensing in particular. Regardless, sensors will continue to penetrate further into everyone's lives and communities, and rendezvous will play an important role in aggregating and enhancing data from individuals to produce information that benefits society. C


## Acknowledgments

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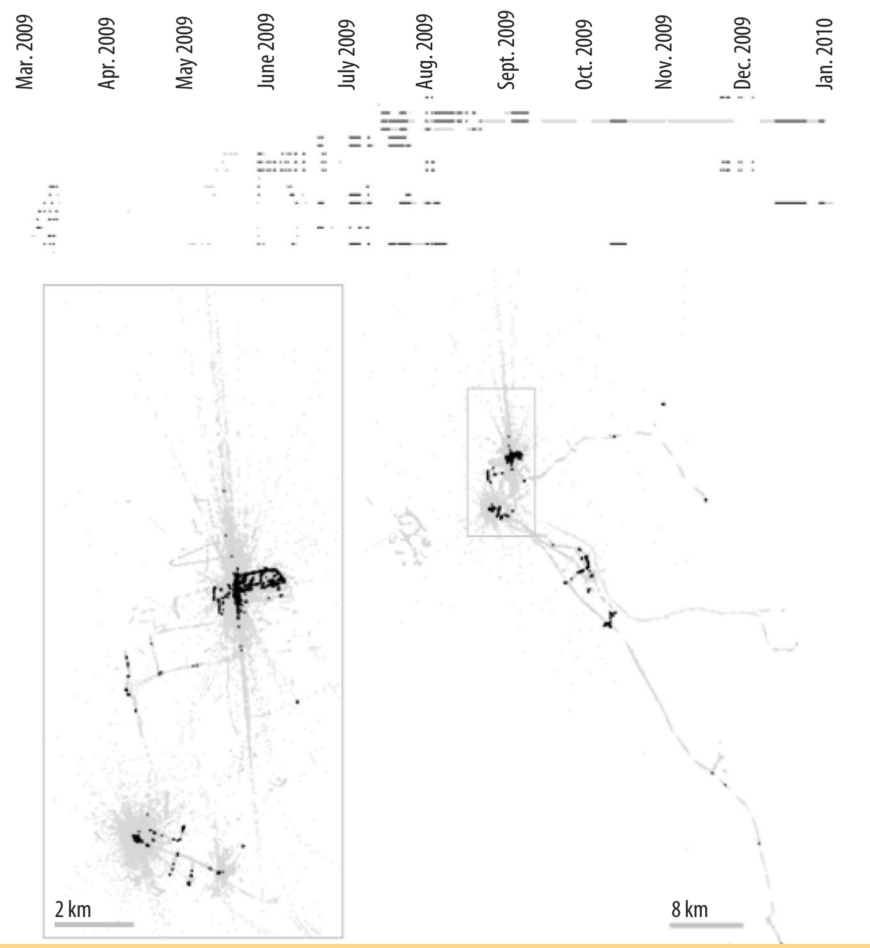


**Figure 5.** Rendezvous points (black) superimposed on all locations (gray) in the Oakland study. Sample times for each sensor appear at top; rendezvous points are in black, and all sample times in gray. As in the Ghana data, rendezvous happen in hot-spot locations, rather than distributed throughout the map. They are not isolated to a few lucky coincidences, but distributed throughout the study in time and space. The stars represent GPS error.

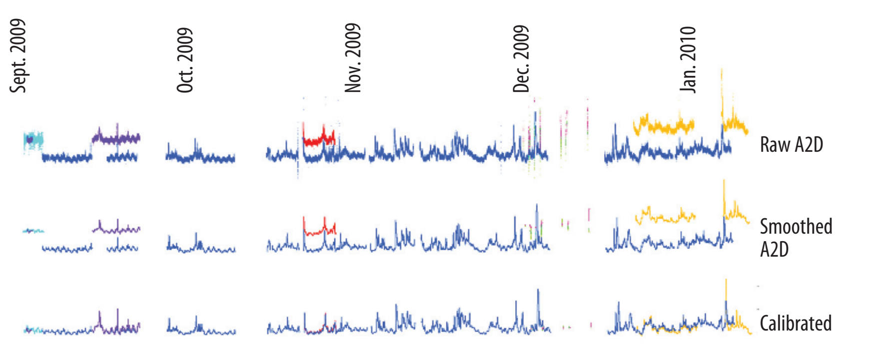


**Figure 6.** The top row shows raw data from the Intel badges' ADC versus time. Colors represent different sensors. The bottom row shows the same data after calibrating each sensor using the research algorithm, and smoothing the data to distinguish the different sensors. As expected, this data shows roughly the same readings, since the ambient pollution concentration is relatively constant over the study area. The middle plot shows uncalibrated data after smoothing. The calibrated data is missing an absolute reference, so no concentration value is indicated.

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# IT Footprinting—Groundwork for Future Smart Cities

Sumi Helal, *University of Florida*

**The goals for developing smart cities are clear and convincing, and the technology is promising and exciting, but achieving these goals requires a massive IT footprinting process.**

Recent advances in pervasive and ubiquitous computing provide a glimpse into the future of our planet and reveal exciting visions of smart cities, homes, workplaces, hotels, schools, and much more.

Driven by a technological evolution offering "low-power many things and wireless almost everything"—for example, IEEE 802.15.4 radio, wireless sensor networks, and sensor platforms—we could, in only a decade, envision and prototype impressive smart-space systems that improve quality of life, enhance awareness of resources and the environment, and enrich user experiences.

For most of these systems, the goals are clear and convincing. But prototyping is one thing—commercial proliferation and creating a new industry are another.

## THE PATH TO SMART CITIES

In particular, many governments around the world are pursuing the development of smart cities. Driven by increasing urbanization and serious economic and environmental challenges, smart cities are emerging as a way to offer technology solutions to bridge the widening gap between supply and demand while reducing urbanization's impact on the environment. This effort also offers an opportunity to recover from the effects of the global recession by creating new green industries and businesses.

Yoshiaki Kushiki, corporate advisor to Panasonic Corporation, points to an important requirement for such new industries to succeed: consumers must also change by choosing "spiritual richness" over "material affluence." This is a valid observation because most of the products and services in smart cities will offer intangible benefits such as energy savings, sustainability, and reduced $CO_2$ emissions in contrast to a "materials only" approach—for example, acquiring the newest and fanciest iPhone on the market.

In principle, the path to smart cities is obvious—embed sensors, actuators, or computers into objects and spaces that make up the smart city's important elements. This "smartening" approach is not new, having driven the embedded systems industry for more than two decades. What's new here are the massive scale and the new ecology that the smartening process requires.

## MASSIVE SCALE

Smartening an entire city is a massive IT footprinting process. To appreciate the scale, think about these questions. How many people live in a large city? How many homes, apartment buildings, and office buildings are there? How many electricity meters? How many wall power plugs? How many cars and parking spots? This is a sample set, but the list could grow very large, and the total number of objects and spaces that will have to be smartened could easily number in the hundreds of millions.

The smart grid alone—an essential part of most envisioned smart cities—will require installing a smart meter in every structure drawing electric power, thereby injecting tens of millions of sensing devices into the cyber-physical infrastructure. The smart grid will also require other controllers that integrate the electrical grid with the IT infrastructure, starting from the supply side, passing through the distribution networks, and ending at the demand side.


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Developing smart cities may start with the smart grid, but it doesn't end there. CO2 zero-emission homes and net-zero-energy buildings may necessitate additional IT footprints. Plug-in hybrid and electric vehicles will also require IT footprinting in the form of in-dash PCs. In addition to energy, other concerns such as healthcare, elder care, education, security, public safety, smart transportation, entertainment, and emergency response will require massive IT footprinting.

## NEW ECOLOGY

But do we have all the ingredient technologies for such massive IT footprinting? Unfortunately, the answer is no. Achieving this objective requires rethinking embedded computing's role and goals. Existing embedded operating systems (OSs), for example, will need to change. They're currently focused only on smartening an object or a device—they're smart but introverted. They don't know about the cloud or the edge devices in between.

To put it another way, current embedded OSs are for smart cities what DOS was for the PC in the early 1980s. We need a new breed of embedded OSs capable of natively and autonomically integrating, connecting, and programming enormous numbers of sensors to the cloud. Without this fundamental change, the IT footprint will simply look like a massive array of stovepipes that needs an army of engineers to integrate it, no matter how smart each individual pipe is.

Advances in hardware are also required. Common components and subsystems will need to enter the marketplace at a faster pace. Memory cards are an example of an industry that has successfully followed this model. Developers will need to tightly integrate more "brain" and communication elements into common modular components in useful packages and form factors. Perhaps what's needed is an ecosystem parallel to the auto parts industry, offering the same standardized functional part in various forms, sizes, and shapes.

Once IT footprinting is enabled, adding point-of-service delivery and interaction platforms such as set-top boxes, smartphones, and public displays will complete the necessary infrastructure for smart-city rollouts. Then, a new world of powerful and serious applications and services will be unleashed, making the app store as commonplace as the local grocery store or Facebook.

This special issue offers four articles on smart cities covering the IT perspective, applications and services, interaction and user experience enrichment, and a fast-progressing smart-city initiative in South Korea.

The topic will obviously be revisited in the future to assess progress and refine our understanding of the changing landscape of goals and requirements. We look forward to your active participation in this area and to receiving your future contributions on this topic.

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# Smarter Cities and Their Innovation Challenges

Milind Naphade, Guruduth Banavar, Colin Harrison, Jurij Paraszczak, and Robert Morris, *IBM*

**The transformation to smarter cities will require innovation in planning, management, and operations. Several ongoing projects around the world illustrate the opportunities and challenges of this transformation.**

Cities are experiencing unprecedented socioeconomic crises. Urban growth and migration are putting significant stress on city infrastructure as demand outpaces supply for water, energy, transportation, healthcare, education, and safety. To reduce costs, improve efficiencies, and deliver the quality of life citizens expect while balancing budgets, cities are increasingly looking to information and communications technology (ICT) and new working practices.

The transformation to smarter cities will require innovation in planning, management, and operations. Several ongoing projects in Brazil, the US, Denmark, South Korea, and other countries illustrate the opportunities and challenges of this transformation.

## NEED FOR SMARTER CITIES

There is an urgent need for cities worldwide to become smarter in how they manage their infrastructure and resources to cater to the existing and future needs of their citizenry. Concurrent trends in urbanization, economic growth, technological progress, and environmental sustainability are the drivers for this newfound urgency.

### Urbanization

More than 50 percent of the world's population now lives in cities. By 2050, the UN forecasts this number to increase to 70 percent due to growth in the current urban population and migration from rural areas.[1] Some of this growth will be in 27 megacities with greater than 10 million people, but more than half of this growth will occur in cities that currently have fewer than 500,000 people. Urban infrastructure already experiencing stress will be hard-pressed to provide even basic services, while emerging cities will face greenfield development challenges.

### Economic growth

The top 100 urban conglomerations currently account for 25 percent of the worldwide gross domestic product. By bringing people together, cities stimulate creativity and entrepreneurship, which further spurs economic activity. While the developed world has underinvested in its cities, the developing world by some estimates will need $40 trillion by 2030 for its new urban infrastructure, which presents tremendous innovation opportunities.

### Technological progress

ICT advances have revolutionized all aspects of life. Two billion people use the Internet, and more than five billion are mobile subscribers.[2] There are 30 billion RFID tags embedded in our world and a billion transistors per human, each costing one ten-millionth of a cent.[3] This convergence of pervasive sensing and networking, wireless connectivity, and cheaper, faster, smaller computers has made it easier to intelligently control systems and empower people.

### Environmental sustainability

There is evidence that human activity has caused unprecedented environmental change, and population growth will soon stress the world's natural resources to the breaking point. Global warming, air pollution, land degradation, declining per-capita availability of fresh water, food shortages, and reduced biodiversity are some of the starkest challenges. Top priorities for cities include sustain-


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ing water, energy, and food supplies, managing waste (95 percent of cities still dump raw sewage into their waters), and reducing greenhouse gas emissions.

Contrary to popular opinion, urban life is often greener than suburban and rural life: inhabitants consume less energy and space for living and use less energy for transportation. In developed societies, urban inhabitants are less dependent on fossil fuels and make more journeys on foot than those living in less densely populated areas.

## SMARTER CITY TRANSFORMATION

It can take a decade for a city to become truly smart. Sometimes the impetus for transformation is recovery from a natural disaster, an impending large-scale event, or a sizable government investment. At other times visionary city leaders galvanize the citizenry and business community to channel their energy and resources into such a project.

### Assessment

Once it has decided on transformation, a city must evaluate its needs and innovation opportunities, set clear objectives, prioritize development efforts, and establish metrics that let city planners, ICT consultants, and residents assess progress.

IBM and other organizations have created several tools to facilitate this process[4] including the Smarter City Assessment Tool, the Actionable Business Architecture, and the Municipal Reference Model. Researchers can use IBM's Component Business Model to partition a city into independent operational units, and they can apply its Smarter City Maturity Model to various domains ranging from resident-oriented services, such as social services and public safety, to structural functions, such as road maintenance and traffic management.

Assessment should be flexible enough to let cities choose the domains most important to them and provide some means of projecting costs and measuring progress—for example, how well various agencies are integrating operations and sharing data. Applying maturity models to numerous cities has also revealed common patterns that can help guide investment strategies and predict the outcome of adopting a particular approach. For example, investing heavily in road expansion without a smarter transit policy can reduce the use of public transportation.

### A 'system of systems'

As Figure 1 shows, at the highest level, a smarter city integrates and optimizes a set of interdependent public and private systems to achieve a new level of effectiveness and efficiency. These systems are increasingly both producers of information and consumers of one another's information, although interactions can also be indirect. Hence, a smarter city can be viewed as a "system of systems."

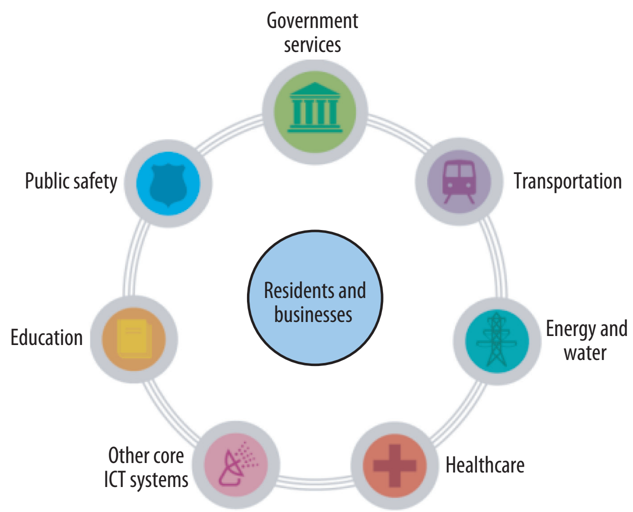


**Figure 1. A smarter city constitutes a "system of systems"—a set of interdependent public and private systems that the city can integrate and optimize to achieve a new level of effectiveness and efficiency.**

Smarter city transformation relies on the use of powerful analytical techniques to extract insights from real-world events to improve urban business processes. These processes can be broadly divided into planning, management, and operations.

**Planning.** A smarter city provides urban planners with tools to exploit various sources of information about human behavior to aid in the allocation of resources—land, water, transportation, and so on—as the city evolves. Holistic modeling of the city's ecosystem provides quantitative support for strategy development, performance evaluation, identification of emerging best practices, and integration of initiatives. Analyzing data from other comparable cities can help planners calibrate urban dynamics models and compare their relative progress.

**Management.** A smarter city can coordinate infrastructure management activities—the creation and maintenance of roads, equipment, and other assets—by providing cross-agency visibility of planned interventions. For example, the electrical utility's replacement of a cable under a street intersection might offer traffic managers an opportunity to save money by replacing a signal at the same location. By providing a time dimension, smarter city data can reveal historical views of each domain and enable managers to project its evolution.

**Operations.** A smarter city integrates multiple data sources to represent the interdependence of urban domains in real time. For example, electrical utilities can combine sophisticated models of near-term demand based on historical usage patterns (day of week, holidays, local weather, major events, and so on) with real-time traf-

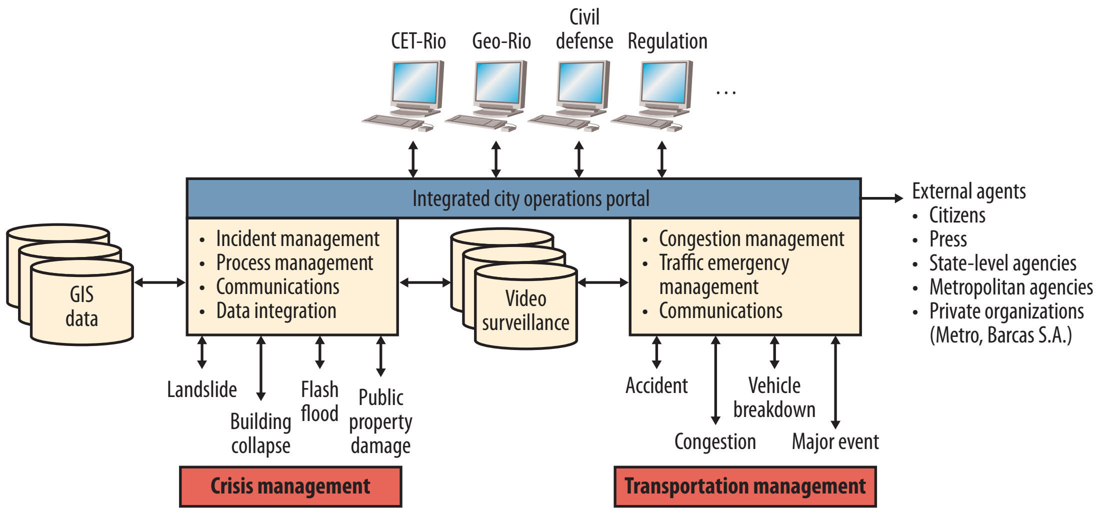


**Figure 2.** Rio de Janeiro's Operations Center integrates dynamic, real-time data and multiple systems to improve crisis and transportation management.

fic information that could impact future demand. Thus, awareness of a major delay in outbound commuter traffic in the early evening could let the utility project a delay in demand because those commuters will arrive home late. The utility could likewise use real-time weather data to predict the location of cables damaged in a rainstorm.

## EXAMPLE SMARTER CITIES

Examples of cities of various size, geography, and economy illustrate different aspects of smarter city transformation.

### Rio de Janeiro, Brazil

Every summer, Rio de Janeiro faces the consequences of intense rainfall, including landslides and flooding. In April 2010, the region endured one of the worst series of torrential rainstorms in decades, in which mudslides killed more than 200 people, left tens of thousands homeless, and caused more than $13 billion in damage (http://en.wikipedia.org/wiki/April_2010_Rio_de_Janeiro_floods_and_mudslides). The resulting chaos, loss of life, and destruction of property motivated state and city authorities to implement advanced ICT capabilities in Rio to better manage disasters and emergencies as well as planned events of national importance.

Using a substantial monetary investment resulting from the city's selection to host the 2014 World Cup and the 2016 Summer Olympics, and under the visionary leadership of Rio's mayor, Eduardo Paes, the city has embarked on an ambitious program to connect multiple systems to improve crisis and transportation management.

The Rio Operations Center[5] opened in December 2010. As Figure 2 shows, it includes an incident management system that will help the city to prepare for and respond to flood-related incidents and a process management system through which multiple agencies can make coordinated and intelligent decisions based on dynamic data from weather sensors, video surveillance, and field personnel, overlaid on a comprehensive geographic information system (GIS). As this system evolves, researchers can integrate data from transportation systems, buildings, and possibly energy, water, and other subsystems into the Rio Operations Center to create a true closed-loop system.

### Dubuque, Iowa

The city of Dubuque is an example of a smarter city in which an economic crisis motivated a transformation. Following the demise of the wood-milling industry in the 1980s, this city of 60,000 has evolved into a vibrant hub of sustainable development by using ICT to optimize resources and operations for its citizens and city management. This has led to one of the fastest urban economic turnarounds in the US, with a diversified workforce and local industries working to make water, energy, and buildings sustainable.

In 2006, Dubuque created a sustainability model with three major themes: economic prosperity, sociocultural vibrancy, and environmental integrity. The model was based on 11 core principles including smart use of energy, water, and other resources; green buildings; reasonable mobility; and greater community knowledge.

Three years later, Dubuque partnered with IBM to become a living lab for smarter city sustainability management that monitors water and electricity consumption in homes using smart meters and provides guidelines and incentives to residents to optimize their individual consumption.[6] Figure 3 shows the citizen dashboard for integrated sustainability management.

Dubuque has been a pioneer in putting citizens at the center of smarter city transformation, a vital aspect that is often ignored. The city also integrates planning, management, and operations both to minimize its carbon footprint and to encourage economic growth.

## Bornholm, Denmark

On Bornholm, Denmark, an island of 40,000 inhabitants, international researchers are developing a system that integrates electric vehicles (EVs) into the local power grid, which relies heavily on renewable wind power. As Figure 4 shows, the EDISON system—Electric Vehicles in a Distributed and Integrated Market Using Sustainable Energy and Open Networks (www.edison-net.dk)—includes a network of public and personal charging stations and integrated technologies to manage the charging of EVs as well as load balancing, billing, and so on.

In addition to reducing carbon dioxide emissions, EVs can act as supplemental storage devices that send power back to the grid when needed. Offshore wind power provides 20 percent of Denmark's electricity, and as part of a long-term strategy to increase that figure to 50 percent, the government hopes to deploy some 200,000 EVs nationwide by 2020.[7]

## Songdo IBD, South Korea

Seoul, the capital of South Korea, already has an advanced ICT infrastructure that provides inexpensive, superfast broadband access to its more than 24 million citizens from virtually anywhere within the city limits. In addition to accelerating the country's economic growth, this universal connectivity has transformed governance, resulting in the world's most advanced and efficient e-government.[8] Among the many benefits of this transformation is greater transparency—the online disclosure of all bids for government contracts has significantly reduced corruption.

Work is now under way on the Songdo International Business District (www.songdo.com), a ubiquitous ecological (u-eco) city 40 miles west of Seoul on reclaimed land in the Incheon Free Economic Zone. When completed in 2015, Songdo IBD will include 80,000 apartments, 50 million square feet of office and retail space (including the 68-story Northeast Asia Trade Center, the tallest building in the country), a hospital, arts and convention centers, an

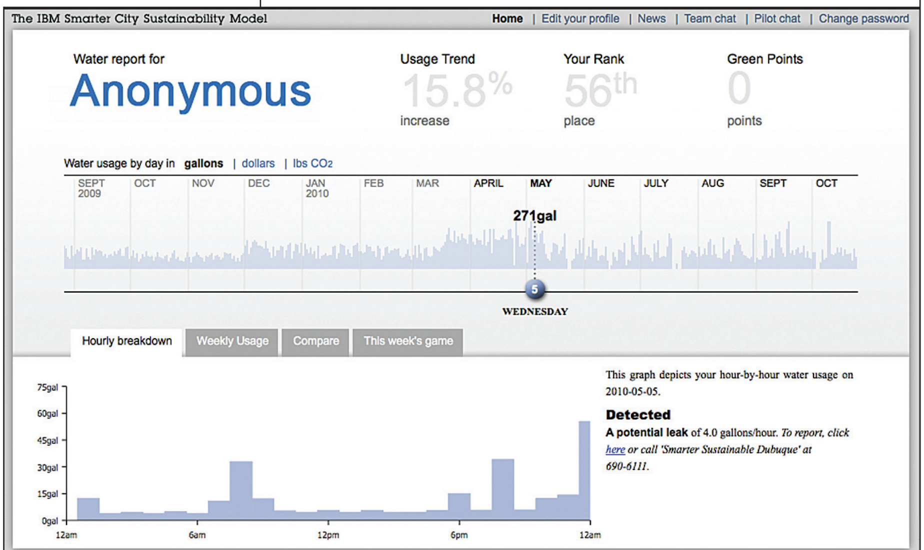


**Figure 3. Citizen dashboard for integrated sustainability management in Dubuque, Iowa.**

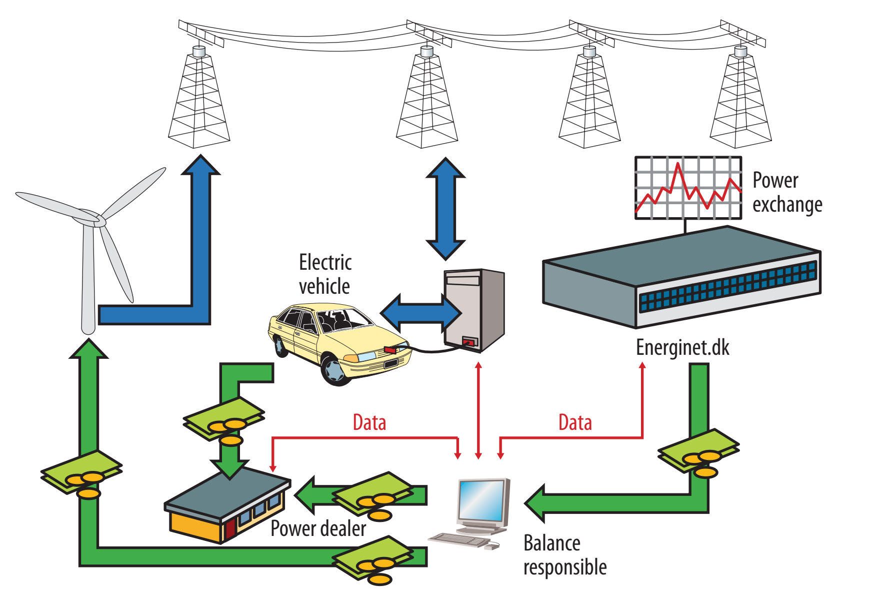


**Figure 4. On the Danish island of Bornholm, the EDISON project—Electric Vehicles in a Distributed and Integrated Market Using Sustainable Energy and Open Networks—is developing a system that integrates electric vehicles into the local power grid, which relies heavily on renewable wind power.**

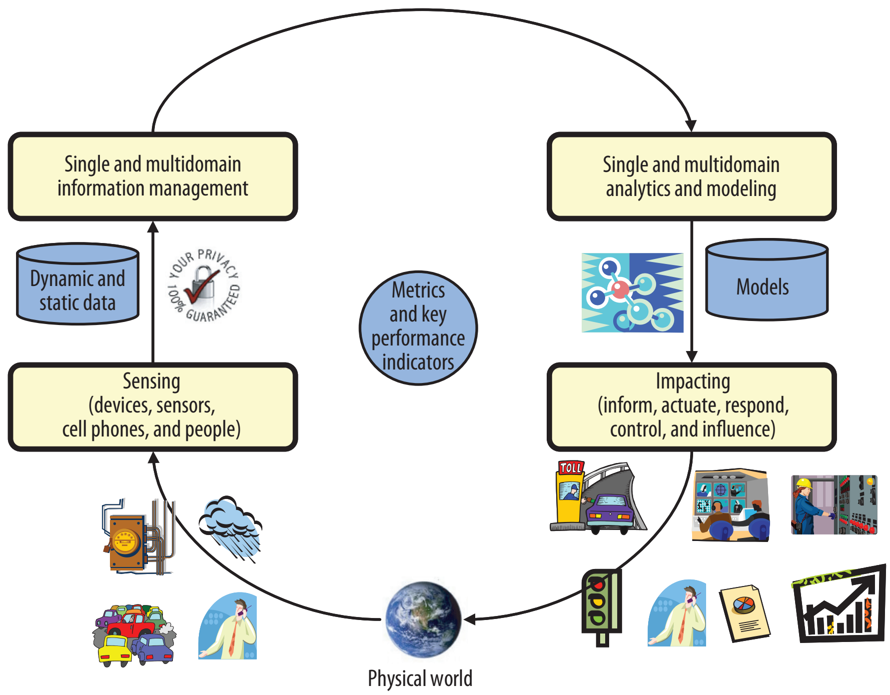


**Figure 5. Smarter cities technology innovation framework. To optimize key metrics and performance indicators, all systems must be integrated in a closed loop.**

academic complex, and 600 acres of open space, making it the largest private real-estate development in history.

A wide-area network of computers will link Songdo IBD's structures and offer citizens and businesses various digital services. For example, individual apartments feature panels in each room that control lighting, temperature, and access to media; 20,000 residential units will feature telepresence technology. A green, state-of-the-art datacenter will help manage all aspects of urban life, from traffic control to water and energy use to recycling.

### Other smarter cities

Many other cities and regions around the world are using technology innovation to improve their planning, management, and operations.

Malta is creating the world's first countrywide smart grid, using ICT to optimize its water and energy systems.[9] Stockholm, Sweden, has implemented a system that automatically charges drivers a fee based on how much they drive (using control points outfitted with lasers and cameras) to reduce congestion and greenhouse gas emissions.[10] India's Gujarat International Finance Tec-City (http://giftgujarat.in/index.aspx) is a greenfield development using advanced technology to, among other things, eliminate discharge waste and achieve 90 percent use of public transit. Portland, Oregon, is using a system dynamics model to discover and coordinate dependencies among key city systems. And Singapore is aspiring to become an innovative technology leader by using ICT to achieve water sustainability and to manage traffic and energy.

## INNOVATION CHALLENGES

Figure 5 illustrates the ideal of a smarter city as a closed loop of interconnected city systems. These systems can be characterized by function: sensing, information management, analytics and modeling, and influencing outcomes. To optimize key metrics and performance indicators, all of these systems must be tightly integrated.

### Sensing a city and its inhabitants

A city is full of sensors—smart water and electric meters, mobile phones, GPS devices, traffic sensors, parking meters, pipe sensors, weather sensors, building sensors, and so on. Even people can be sensors—using crowdsensing to gather intelligence on city operations is an emerging research area. The main innovation challenges in sensing a city and its inhabitants are trading off cost with quality and dual usage, and ensuring privacy and security.

**Cost versus quality.** Cheap, ubiquitous sensors can be used in large numbers, but their noisy, low-quality signals impose a nontrivial burden on analytics systems and might also require frequent calibration and diagnostic evaluation. In contrast, high-cost sensors with embedded intelligence can make analysis simpler and more accurate, and may be self-calibrating and -diagnosing, but cannot be installed in the quantities needed to cover large areas.

**Cost versus dual usage.** A sensor used for purposes for which it was not originally intended will not yield high-quality data, but replacing it with the proper sensor or augmenting it with another sensor can be prohibitively expensive.

Dubuque, for example, uses smart electric meters in homes to aggregate resource consumption at 15- or 60-minute intervals. Originally designed for billing and dynamic pricing, these meters are not as accurate as having a sensor on every electrical device. Disaggregating energy use for each house requires sophisticated analytics but is currently cheaper than instrumenting homes with a large number of localized sensors. This problem could be alleviated if future appliances have built-in functionality to report their energy consumption to home-area networks.

Another example is the use of mobile phones for location sensing. Mobile phones can be used to estimate users' locations through the data generated at cell towers. This is an inexpensive way to measure positional data and enables a plethora of smarter city applications such as traffic management and emergency response—a particularly attractive option for a developing economy—but its high range of error would require sophisticated analytics.

**Privacy.** The sensors that produce the best data and enable the most effective modeling are also the most intrusive, and thus more likely to make inhabitants of the environment being sensed uncomfortable. This is another reason why putting energy-monitoring devices on every home appliance is currently impractical.

**Security.** Significant research is needed to ensure that both sensors and actuators are secure when it comes to the acquisition, storage, and transmission of information. Tampering with or snooping on sensed data could result in nightmarish scenarios ranging from thieves knowing when residents are not at home to terrorists turning off a city's power and water. Cybersecurity must be taken to a new level before sensors can be deployed on a massive scale.

## Managing information across all city systems

The main research challenges in managing smarter city data are the need for common information models and the ability to safely share information across multiple agencies within a city and among multiple cities in a metropolitan region.

**Information models.** To ensure end-to-end visibility while managing smarter city infrastructure and services, it is necessary to integrate data from disparate sources, each with its own sampling frequency, latency characteristics, and semantics. For example, information related to roads is scattered across many agencies including transportation, urban planning, public works, emergency services, public safety, and environmental management.

Creating and applying a unified information model makes it possible to obtain a more complete picture of urban activity. The ability to understand how combinations of factors contribute to, say, a rapid increase in the demand for water or an unusually high accident rate on a stretch of road in turn facilitates better operational decisions.

A principal technology base for managing spatial information and entities in cities is a GIS with associated databases and mapping tools. In the future, this model will be extended to include not only static data such as topography, land use, and the built environment but also dynamic information such as service delivery, resource consumption, and the movement of people (which can be used to infer behavior), vehicles, and freight.

**Privacy, security, and access control.** Securing data from sensed urban environments is a major research challenge. City datacenters constitute the largest potential single point of failure and thus require the most stringent security. Authorities must also design and implement privacy policies to prevent unauthorized access to data. In addition, access control mechanisms must be in place to ensure that visualization, analytics, and modeling applications do not misuse data. For example, mobile phone data used to sense traffic congestion with the explicit approval of the devices' owners should not be used to issue speeding citations.

Securing and controlling access to a plethora of data streams and applications will require a fairly agile, real-time implementation engine. New models are also needed to encourage the utmost transparency within required constraints.

**Creating and applying a unified information model makes it possible to obtain a more complete picture of urban activity.**

**Standards and interoperability.** Different cities and even different agencies within the same city adopt different models to manage information. Some industries, such as the electrical utility industry, have a well-developed set of standards, while others, such as the water utility industry, seem unaware of the concept. Initiatives like the Municipal Reference Model,[11] developed by the Municipal Information Systems Association of Canada, aim to incorporate the perspectives of the many stakeholders involved in urban infrastructure and services. More such models should be developed and refined through an open industry process.

## Observing and understanding city activity

The availability of massive amounts of sensed information opens up fascinating opportunities to understand city activity through modeling and analytics. This will require real-time and batch analysis of heterogeneous data with cross-domain dependencies in the presence of significant uncertainty and variability.

**System models.** Models of city systems must be statistical as well as physical. For example, Dubuque and Malta model resource consumption at both the individual and community level, Stockholm models traffic congestion, and Denmark's EDISON project models wind power generation and EV-based energy storage. Traffic management, emergency response, and other such services in Rio rely on weather prediction models.

The challenge in building such models is the lack of ground-truth data to accurately calibrate and train them. Models need to be bootstrapped with existing data and adaptable to changes in the state of the city. Another set of challenges revolves around the difficulty of predicting human behavior—for example, how residents will respond to green incentives.

**Analytics.** By studying how its systems interact with one another and with users over a long period of time, a city can operate its infrastructure and services more effectively—the equivalent of a company applying enterprise resource planning. Recurring patterns, anomalies, and evolving events in models can reveal important insights, and "what if" scenarios can help in planning.

For example, Stockholm's traffic congestion models enable better road-use charging policies, Rio's fine-grained rainfall prediction models facilitate emergency planning and traffic management, Singapore is using sophisticated traffic models to optimize transportation operations, and Dubuque's energy consumption models help Iowa's utility board and energy independence office perform statewide energy policy planning.

## Influencing outcomes

The ultimate goal of introducing smarter city technology is to optimize control of city systems and to offer citizens both a wider range of choices and real-time feedback to influence their behavior and thus obtain better outcomes.

**Optimal system control.** Conceptually, a smarter city can be viewed as an interdependent collection of closed-loop systems. At the physical engineering level, a closed-loop system can be likened to a process control system automatically (except in extreme cases) regulated through appropriate feedback and control. At the decision support level, a closed-loop system is automated to a limited degree through the application of rule-based models.

Optimizing resources across all systems as well as within each subsystem is a challenging problem that must address cross-domain and cross-system dependencies that may also be cyclic. In the EDISON project, for example, grid electricity capacity in part depends on how much power EVs store, but the energy they feed back to the grid depends on their usage, which in turn depends on traffic congestion. Managing energy generation and storage and managing vehicle use are each difficult, but optimizing the two systems together is a highly complex cross-domain resource optimization problem. Ensuring fail-safe operations of interdependent systems is also critical.

**Human-city interaction.** People are at the center of a city's transformation into a smarter city. They are important sources of data, both about themselves and about the physical world, and can become willing participants if they can easily provide the data—for example, through mobile phones—and if they see the value of the information resulting from their contribution. While information models and analytical algorithms can organize data, provide insights, and make simple decisions, it will be up to humans to make the complex decisions.

Modeling, understanding, and influencing human behavior, providing location-aware information and feedback, and cultivating trust in smarter city technologies are key challenges that will draw on work in psychology, user experience design, urban systems, location-aware services, game design and game theory, and social computing.

Research will focus on what information to present to users, when and how to present it, and what reactions to expect. It will also explore how to motivate positive behavioral change. For example, Dubuque matches 50 percent of the costs of fixing household water leaks if users report the leaks and follow through on repairs, and its insightful feedback on water consumption has increased conservation by 10 percent. Likewise, Seoul is using its citywide Internet connectivity to incentivize use of public transit by providing online information to drivers about insurance discounts, reduced-cost parking, and a tax break for leaving their cars at home one business day a week.

Cities must get smarter to address an array of emerging urbanization challenges, and as the projects highlighted in this article show, several distinct paths are available. The number of cities worldwide pursuing smarter transformation is growing rapidly. However, these efforts face many political, socioeconomic, and technical hurdles.

Changing the status quo is always difficult for city administrators, and smarter city initiatives often require extensive coordination, sponsorship, and support across multiple functional silos. The need to visibly demonstrate a continuous return on investment also presents a challenge. The technical obstacles will center on achieving system interoperability, ensuring security and privacy, accommodating a proliferation of sensors and devices, and adopting a new closed-loop human-computer interaction paradigm. ■

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