

Mobile Computing: the Next Decade

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In the inaugural issue of MC2R in April 1997 [24], I highlighted the seminal influence of mobility in computing. At that time, the goal of “information at your fingertips anywhere, anytime” was only a dream. Today, through relentless pursuit of innovations in wireless technology, energy-efficient portable hardware and adaptive software, we have largely attained this goal. Ubiquitous email and Web access is a reality that is experienced by millions of users worldwide through their Blackberries, iPhones, iPads, Windows Phone devices, and Android-based devices. Mobile Web-based services and location-aware advertising opportunities have emerged, triggering large commercial investments. Mobile computing has arrived as a lucrative business proposition.

Looking ahead, what are the dreams that will inspire our future efforts in mobile computing? We begin this paper by considering some imaginary mobile computing scenarios from the future. We then extract the deep assumptions implicit in these scenarios, and use them to speculate on the future trajectory of mobile computing.

I. Scenario 1: Lost Child

Five-year old John is having a wonderful time with his family at the Macy’s Thanksgiving Day parade in Manhattan. Mid-way through the parade, John sees a group of friends in the crowd nearby. He shows his parents where his friends are, and tells them he is going over to meet them. Since his parents see responsible adults in the group, they are fine with John walking over to see his friends. An hour later, John’s parents walk over to where they expect to find him. To their shock, they discover that the friends have not seen John at all. He has been missing for an entire hour now, and John’s parents are very concerned. Searching for a lost child in a Manhattan crowd is a daunting task.

Fortunately, a police officer nearby is able to send out an amber alert via text message to all smartphone users within two miles. He requests them to upload all photographs they may have taken in the past hour to a secure web site that only the police can view. In a matter of minutes, the web site is populated with many photographs. New photographs continue to arrive as more people respond to the amber alert.

With John’s parents helping him, the police officer searches these photographs with an application on his smartphone. His search is for the red plaid shirt that John was wearing. After a few pictures of Scottish kilts in the parade, a picture appears that thrills John’s parents. In a corner of that picture, barely visible, is a small boy in a red shirt sitting on the steps of a building. The police officer recognizes the building as be-

ing just two blocks further down the parade route, and contacts one of his fellow officers who is closer to that location. Within moments, the officer is with the boy. John is safe now, but he has a lot of explaining to do . . .

II. Scenario 2: Disaster Relief

The Big One, measuring 9.1 on the Richter scale, has just hit Northern California. The entire Bay Area is one seething mass of humanity in anguish. Many highways, power cables and communication lines are severely damaged. Internet infrastructure, including many key data centers, have been destroyed. The Googleplex has been reduced to a smoking hulk. Disaster on such a scale has not been seen since World War II.

In spite of heroic efforts, disaster relief is painfully slow and hopelessly inadequate relative to the scale of destruction. First responders are guided by now-obsolete maps, surveys, photographs, and building floor plans. Major highways on their maps are no longer usable. Bridges, buildings, and landmarks have collapsed. GoogleEarth and GoogleMaps are now useless for this region. Conducting search and rescue missions in the face of this obsolete information is difficult and dangerous. New knowledge of terrain and buildings has to be reconstructed from scratch at sufficient resolution to make important life and death decisions in search and rescue missions. Time is short. In desperation, the rescue effort turns to an emerging technology: camera-based GigaPan sensing. Us-

ing off-the-shelf consumer-grade cameras in smartphones, local citizens take hundreds of close-up images of disaster scenes. Transmission of these images sometimes occurs via spotty low-grade wireless communication; more often, the images are physically transported by citizens or rescue workers. The captured images are then stitched together into a zoomable panorama using compute-intensive vision algorithms. To speed up the process, small GigaPan robots that can systematically photograph a scene with hundreds of close-up images are air-dropped over the area for use by citizens.

Slowly and painstakingly, detailed maps and topographical overlays are constructed bottom-up. As they become available, rescue efforts for those areas are sped up and become more effective. Rescuing trapped people is still dangerous, but at least the search teams are now armed with accurate information that gives them a fighting chance . . .

III. Scenario 3: Cognitive Assistance

Ron is a young veteran who was wounded in Afghanistan and is slowly recovering from traumatic brain injury. He faces an uncertain future, with a lack of close family nearby and with limited financial resources for professional caregivers. He has suffered a sharp decline in his mental acuity and is often unable to remember the names of friends and relatives. He also frequently forgets to do simple daily tasks. Even modest improvements in his cognitive ability would greatly improve his quality of life, while also reducing the attention demanded from caregivers. This would allow him to live independently in dignity and comfort, as a productive member of his community.

Fortunately, a new experimental technology may provide Ron with cognitive assistance. At the heart of this technology is a lightweight wearable computer built into the frame of Ron's eyeglasses. Integrated with the eyeglass frame are a camera for scene capture and bone-conduction earphones for audio feedback. These hardware components offer the essentials of a system to aid cognition when they are combined with software for scene interpretation, face recognition, context awareness and voice synthesis. When Ron looks at a person for a few seconds, that person's name is whispered in his ear along with additional cues to guide Ron's greeting and interactions; when he looks at his thirsty houseplant, "water me" is whispered; when he look at his long-suffering dog, "take me out" is whispered. Ron's magic glasses travel with him, transforming his surroundings into a helpful

smart environment.

IV. Scenario 4: Medical Consultation

Dr. Jones, a renowned pathologist, is at a restaurant with her family. She is contacted during dinner about a pathology slide that must be interpreted while surgery is in progress on a patient. Viewing the slide on her tiny smartphone screen would be useless. Fortunately, there is a large screen in the lobby that usually displays advertising but is available for brief use by customers. Walking up to the display, Dr. Jones views the slide at full resolution over the Internet. Using her smartphone for control, she is able to zoom, pan and rotate the slide just as if she were at a microscope in her lab. Privacy-sensitive clinical information about the patient is displayed only on the smartphone. Dr. Jones quickly interprets the slide, talks to the surgeon on the phone, and then returns to dinner.

V. Reflecting on these Scenarios

These scenarios embody a number of themes that will be central to the evolution of mobile computing over the next decade. Common to many of these scenarios is the prominent role of mobile devices as *rich sensors*. While their computing and communication roles continue to be important, it is their rich sensing role (image capture) that stands out most prominently in these scenarios. We use the term "rich" to connote the depth and complexity about the real world that is being captured. This is in contrast to simple scalar data such as temperature, time and location that are involved in typical sensor network applications. When cell phones with integrated cameras first appeared, people wondered if they represented a solution in search of a problem. Would mobile users take so many photographs that this capability was worth supporting? Today, the value of this functionality is no longer questioned. Tomorrow, people will wonder why any digital camera lacks the wireless capability to transmit its images. Video capture, leading to even richer sensing and recording of the real world is also likely to gain traction.

Crowd sourcing, the second emergent theme, amplifies the power of rich sensing. Scenarios 1 and 2 benefit from the voluntary participation of large numbers of smartphone users. The importance of crowd sourcing as a fundamental technique in mobile computing is already well-recognized, as shown by a sampling of recent papers in mobile computing conferences and workshops [4, 11, 18, 34, 35, 36]. This



(a) Panorama



(b) Full Zoom

Figure 1: GigaPan Image of Hanuama Bay, Hawaii (May 19, 2008)



(a) Panorama



(b) Full Zoom

Figure 2: GigaPan Image of Downtown Port Au Prince, Haiti (January 29, 2010)

emergent theme is likely to spawn new research in topics such as rapid service discovery, security and privacy, integration with social networking mechanisms such as Facebook, and incentive mechanisms such as micro-payment systems.

Another emergent theme is *near-real-time data consistency*. This is most apparent in the lost child scenario, where the only useful images are very recent ones. Pictures taken before the child was lost are useless in this context. Recency of data is also important in the disaster relief scenario. A major earthquake is often followed by aftershocks for hours or possibly days. These aftershocks can add to the damage caused by the original quake, and in some cases be the “tipping point” that triggers major structural and topographical changes. Regions that have already been mapped after the original quake may need to be remapped. The need for near-real-time data consistency forces rethinking of a long line of work in mobile computing that relates to the use of prefetching and hoarding for failure resiliency. The core concepts behind those techniques may still be valuable, but major changes in their implementations may have to be developed in order to apply them to the new context. In the disaster relief scenario, for example, many old maps and photographs may still be valid if the buildings and terrain involved have only been minimally affected. However, discovering whether it is acceptable to use hoarded information about them is a challenge. No central authority (e.g. a server) can answer this question with confidence. Only an on-the-spot entity (e.g. a user with a mobile device) can assess whether current reality is close enough to old data for safe reuse. That determination may involve human judgement, possibly assisted by software (e.g. a program that compares two images to estimate disruption).

A fourth emergent theme is *opportunism*. This is most evident in the lost child scenario. The users who contribute pictures were completely unaware of their potential use in searching for the lost child. They took the pictures for some other reason, such as a funny float in the parade. But because of the richness of the sensed data, there are potentially “uninteresting” aspects of the image (e.g. small child in the corner of the picture) that prove to be very important in hindsight — it is context that determines importance. Although the theme of opportunism also applies to simpler sensed data (e.g., anti-lock braking devices on cars transmit their GPS coordinates on each activation, enabling a dynamic picture of slick spots on roads to be obtained by maintenance crews), the richness of captured data greatly increases the chances for opportunistic reuse. An airport video image that was deemed uninteresting on 9/10/2001 may prove to be of high interest two days later because it includes the face of a 9/11 hijacker. With such opportunism comes, of course, many deep and difficult questions pertaining to privacy. While these questions already exist today with mining data from surveillance cameras, they will grow in frequency and significance as mobile users increasingly contribute their rich sensed data. One can easily imagine a business model that provides small rewards for contributors of such data, while reaping large profits by mining aggregated data for customers.

A fifth emergent theme is *transient use of infrastructure*. This is most obvious in Scenario 4, which involves transient use of a large display. It is also implicit in Scenario 3, where augmented reality is used as assistive technology. One of the earliest practical applications of pervasive computing was in the creation of *smart spaces* to assist people. These smart spaces are located in custom-designed buildings such as the Aware Home at Georgia Institute of Technol-

ogy [17], the Gator Tech Smart House at the University of Florida [13], and Elite Care’s Oatfield Estates in Milwaukie, Oregon [30]. These sensor-rich environments detect and interpret the actions of its occupants and offer helpful guidance when appropriate. Instead of relying on sensors embedded in smart spaces, Scenario 3 dynamically injects sensing into the environment by enabling interpretation of the surroundings through computer vision on a mobile computer. Using computer vision for sensing has two great advantages. First, it works on totally unmodified environments — smart spaces are not needed. Second, the sensing can be performed from a significant physical distance. However, sensing the environment alone is not sufficient; it is also necessary to accurately sense user context. This can be done using low-cost body-worn sensors and activity inferencing via machine learning techniques to obtain user context. This combination of computer vision and activity inferencing enables a user-centric approach to cognitive assistance that travels with the user and is therefore available at all times and places. With this approach, the forces driving improvements are largely related to Moore’s Law rather than to public investments in physical infrastructure. Although tantalizingly simple in concept, the computational requirements of this “carry your sensing with you” approach forces the architectural changes discussed in the next section.

These scenarios also suggest the need to broaden our definition of “mobile computing” to embrace developments that lie well outside our narrow historical concerns. Examples include GigaPan technology in the disaster relief scenario, and real-time image search in the lost child scenario. These may feel like science fiction, but they are reality today.

For example, consider GigaPan technology. Figure 1(a) shows a 5.6 gigapixel panorama that has been stitched together from 378 individual images captured with a consumer-grade digital camera. The software available for navigating such an image allows a user to probe the panorama at very high zoom levels, much like GoogleEarth. This image, and many others, can be explored at the GigaPan web site (<http://www.gigapan.org>) [32]. The level of detail can be astonishing. For example, Figure 1(b) shows a legible warning sign at a lifeguard station. In Figure 1(a), the entire lifeguard station is barely visible as a speck on the distant beach. Figure 2(a) is relevant to the disaster relief scenario. It shows a panorama stitched together from 225 individual images of downtown Port Au Prince, Haiti that were taken by a news reporter

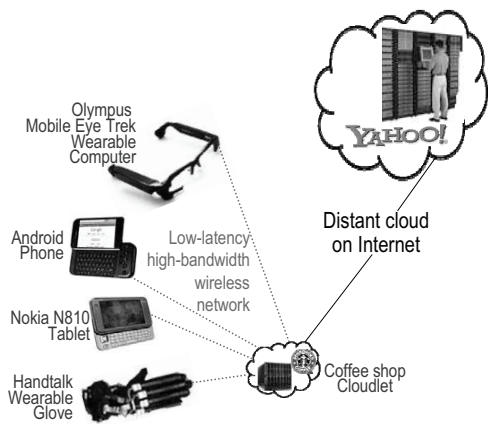
who was covering the earthquake relief effort. These images were stitched together after the reporter’s return to the United States, since the stitching capability was not available at the disaster site. Figure 2(b) shows a zoomed-in view of damaged electrical infrastructure, including the ID number of the tower that has been destroyed. Imagine how valuable this sensing and mapping capability would be if it were available at large scale at a disaster site, very soon after the disaster strikes.

Another example technology that is far off the beaten path of mobile computing is the image search mechanism in Scenario 1. This mechanism must perform near real-time content-based search of image data over the Internet, without an index and without advance knowledge of the search queries. No commercial search engine such as Google, Bing or Yahoo! supports this capability today. However, it has been successfully demonstrated in *Diamond* [1, 27] by shipping query code to the data sources and then dynamically interleaving search processing and result viewing. This is in contrast to the rigid separation of web crawling, index creation and index lookup in today’s search engines. Since there is no index, *Diamond* uses high degrees of CPU and I/O parallelism to generate search results at an acceptable rate and to present them to users as soon as they are discovered. The expertise, judgement, and intuition of the user performing the search can then be brought to bear on the specificity and selectivity of the current search. Although the *Diamond* approach was developed independently of mobile computing considerations, its query-shipping architecture maps well to a low-bandwidth wireless setting. Recent work by Sani et al [23] shows how this approach can be extended to energy-efficient search of recently-captured photos on a collection of 3G-connected smartphones.

VI. Architectural Evolution

Mobile computing has historically assumed a 2-level hierarchy. Originally, the two levels were identified as “servers” and “clients.” More recent terminology uses “cloud” to connote the computational and information resources represented by a collection of servers. Regardless of terminology, however, the 2-level concept is woven quite deeply into our thinking about mobile computing. The upper layer (“cloud” or “server”) is assumed to be well-managed, trusted by the lower layer, and free from concerns that are specific to mobility such as battery life and size/weight constraints.

Future architectures for mobile computing are



(a) Cloudlet Concept

	Cloudlet	Cloud
<i>State</i>	Only soft state	Hard and soft state
<i>Proximity</i>	LAN latency, typically one Wi-Fi hop	WAN latency, across Internet
<i>Network</i>	LAN bandwidth	WAN bandwidth
<i>Sharing</i>	Few users at a time	100s-1000s of users at a time

(b) Key Differences: Cloudlet vs. Cloud

Figure 3: Extending the Classic 2-level Mobile Computing Architecture to 3 Levels

likely to extend this 2-level hierarchy to at least one additional layer, possibly more. The case for an intermediate layer called a *cloudlet* was articulated in a recent paper [26]. The demands of compute-intensive and data-intensive processing within tight latency bounds in a mobile setting, as illustrated by Scenario 3, motivate the need for cloudlets. From a distance, it may appear as if computer vision on mobile computers is a mature technology: after all, many computer vision applications have been developed for mobile devices such as smartphones. However, upon closer examination, the situation is much more complex and subtle. The computational requirements for computer vision tools vary drastically depending on the operational conditions. For example, it is possible to develop (near) frame-rate object recognition (including face recognition [22]) operating on mobile computers *if* we assume restricted operational conditions such as small number of models (*e.g.*, small number of identities for person recognition, and limited variability in observation conditions (*e.g.*, frontal faces only). The computational demands rapidly outstrip the capabilities of mobile computers as the generality of the problem formulation increases. For example, just two simple changes make a huge difference: increasing the number of possible faces from just a few close acquaintances to the entire set of people known to have entered a building, and reducing the constraints on the observation conditions by allowing faces to be at arbitrary viewpoints from the observer. Similar tradeoffs apply across the board to virtually all computer vision applications, not only in terms of computational demands but also in terms of dataset sizes. For example, vision-based navigation techniques based on matching current observations to a large database of images [14, 15] may be able to operate on a laptop for databases of moderate size ($10^3 - 10^5$ images) but will require larger machines beyond that.

Overcoming these computational obstacles on mo-

bile devices is not simply a matter of waiting for a few generations of improvements through Moore’s Law. The design of mobile hardware is constrained by physical considerations such as weight, size and heat dissipation, and by energy conservation features to ensure extended operation on a lightweight battery. Improved design of mobile devices often focuses on these attributes, foregoing raw performance improvement. While a modest rate of improvement in the computational capabilities of mobile devices can be expected, it will be far from adequate to meet the demands of computer vision in its full generality in the near future.

To amplify their computational capabilities, mobile devices can opportunistically offload resource-intensive application execution to compute servers. This approach, called *cyber foraging*, was proposed almost a decade ago [2, 25]. Since then, many aspects of cyber foraging have been investigated [3, 5, 6, 7, 8, 9, 10, 12, 16, 19, 21, 33]. Today, there is substantial consensus in the research community that offloading resource-intensive application execution is a core technique in mobile computing. However, what has not been investigated is the architecture and efficient implementation of the infrastructure necessary to support cyber foraging as a user traverses a substantial geographic area. Without an Internet-scale architecture for cyber foraging, this technique will have limited real-world impact. In particular, we will not be able to rely on cyber foraging to solve the problem of supporting computer vision algorithms in their full generality on mobile hardware.

The recent emergence of *cloud computing* suggests the possibility of leveraging infrastructure such as Amazon’s EC2 cloud or IBM’s RC2 cloud for cyber foraging. Unfortunately, these clouds are concentrated in data centers that are typically far from the mobile user. The long WAN latencies to applications running in the cloud hurt the crisp interaction that is so critical for smooth and non-disruptive cognitive assis-

tance. Humans are acutely sensitive to delay and jitter, and it is very difficult to control these parameters at WAN scale. As latency increases and bandwidth drops, interactive response suffers. This distracts the user, and reduces his or her depth of cognitive engagement. Previous work has shown that latency can negatively impact interactive response in spite of adequate bandwidth [20]. The proximity of cloudlets to users (typically one Wi-Fi hop) solves this problem.

We envision two flavors of cloudlet implementation and placement. If a single building or a proximate collection of buildings already possess a data center and LAN-connected Wi-Fi access points, the easiest approach to deploying cloudlets would be to physically concentrate them in the data center and to connect them to Wi-Fi access points via the wired LAN backbone of the building. This approach would work with unmodified Wi-Fi infrastructure, and has the additional advantage that upgrading a building's cloudlets will be relatively simple since they are located in its data center. The physical security of cloudlets is also easier to safeguard. This flavor of cloudlets can use commodity server hardware, thus keeping their cost low.

For settings that do not have a data center nearby, we envision a second flavor of cloudlet hardware in which processing, memory and storage is integrated with a Wi-Fi access point and physically dispersed just as Wi-Fi access points are today. Figure 3(a) illustrates this flavor of cloudlet deployment. Internally, such a cloudlet may be viewed as a cluster of multi-core computers, with gigabit internal connectivity, wired Internet connectivity and a high-bandwidth wireless LAN for association with nearby mobile devices. This flavor of cloudlet can be viewed as a “*data center in a box.*” It is self-managing, requiring little more than power, Internet connectivity, and access control for setup. For safe deployment in unmonitored areas, such a cloudlet may be packaged in a tamper-resistant or tamper-evident enclosure with remote monitoring of hardware integrity. This second flavor of cloudlets can include cameras for sensing. The additional viewpoints provided by these cameras can augment the viewpoint of a body-worn camera to help resolve ambiguity in vision algorithms. Of course, the presence of cameras dispersed within a building leads to privacy concerns that must be addressed before a deployment.

Figure 3(b) summarizes some of the key differences between cloudlets and clouds. Most importantly, a cloudlet only contains *soft state* such as cache copies of data or code that is available elsewhere. Loss or de-

struction of a cloudlet is hence not catastrophic. This stateless model leads to an important research challenge: how can a mobile device rapidly and safely customize a cloudlet for its specific use? One possible solution involves dynamic virtual machine synthesis [26]. Other approaches may also need to be explored.

Although originally motivated by considerations of network latency, cloudlets have much broader relevance. In particular, they are relevant to both the scenarios presented earlier. The GigaPan approach relies on compute-intensive vision algorithms to stitch together a zoomable panorama from individual images. Under normal conditions, these algorithms can be executed in the cloud. However, cloud computing may be compromised in the aftermath of a disaster. The physical infrastructure necessary for good Internet connectivity may have been destroyed and it may be many days or weeks before these can be repaired. Limited Internet connectivity may be re-established soon after the catastrophic event, but there will be very high demand on this scarce resource from diverse sources: families trying to desperately learn and share information about the fate of loved ones, citizen reporters and professional journalists sharing videos, images, blogs, and tweets of the disaster area with the outside world, and disaster relief agencies coordinating their efforts with their home bases. Under these conditions, cloudlets may be needed to support cloud computing. We envision opportunistic deployment of cloudlets in disaster relief. In the immediate aftermath of a disaster, before external IT supplies have arrived, any available hardware such as an undamaged desktop can be pressed into service as a cloudlet. A cloudlet can even be built around a high-end laptop, with its few hours of battery life being priceless prior to the arrival of emergency electrical generators. As IT supplies arrive, temporary cloudlets may be replaced by purpose-designed equipment and energy sources.

Cloudlets also have relevance to the lost child scenario. In that scenario, the near-real-time image search will require extensive computation since pre-computed indexes are not available for the contributed images. Cloud computing is the obvious answer for this, but exactly where in the cloud to compute is an open question. The task involves submission of images from a lot of people in the immediate neighborhood of the lost child; the search results will also be viewed there. This suggests use of local infrastructure (i.e., a cloudlet) rather than distant infrastructure. Once the search is completed (successfully or unsuccessfully) the contributed images can be discarded.

This fits well with the stateless model of cloudlets and their use as transient infrastructure.

VII. Reducing Distraction

User attention is a resource that is more precious in mobile computing than energy, wireless bandwidth, or other computational resources. The recognition that human attention is a critical resource dates back to the work of Herb Simon over sixty years ago [28]. His 1971 characterization of information overload [29] is especially relevant today: “*What information consumes is rather obvious: it consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention and a need to allocate that attention efficiently among the overabundance of information sources that might consume it.*” The same theme was echoed by Mark Weiser in his characterization of ubiquitous computing as a disappearing technology [31].

Since mobility itself consumes user attention, mobile computing stresses a resource that is often over-committed. Additional demands on user attention are made by emerging business models such as location-based advertising and new capabilities such as mobile social networking. The most successful mobile computing systems of the next decade will be those that are able to reduce or eliminate system-induced distractions such as failures, poor or erratic performance, confusing output, and out-of-context interactions. By trading off relatively plentiful computing resources for this scarcest of resources, the end-to-end effectiveness of systems in human workflows can be greatly improved. This will be the holy grail of mobile computing in the next decade.

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