New Horizons for Mobile Computing

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Abstract

Storage capacity and communication bandwidth are two factors that significantly impact the design and implementation of mobile systems. Furthermore, storage density is increasing at an exponential rate faster than the associated communication bandwidth. High-density storage in very small form factors will enable new classes of applications that would not be possible in systems which rely heavily on communication. These applications, which involve continuous capture, pre-loaded content, and proactive data loading, will help overcome some of the barriers presented to mobile systems. Researchers would be prudent to recognize these trends and better understand how technology growth will impact their research agenda.

Keywords: Ubiquitous Computing, storage capacity, communication bandwidth, mobile applications, future trends**.**

1 Factors for mobile computing

In this paper we examine two dimensions of technology that profoundly affect the design of mobile computing platforms: communication bandwidth and storage density. Memory and communication can to some extent play off against each other. If you are mobile and have a high bandwidth connection to the Internet, then it is less important how much data you are carrying with you; the communication link can be used to acquire the data on demand. On the other hand if the communication bandwidth is small or frequently unavailable, then carrying as much data as possible in the mobile device is desirable, ensuring access even during communication blackouts.

At any given time the state-of-the-art in the capability of storage and communication bandwidth, and the relative costs of each solution, will have considerable impact on the design choices made for commercial mobile systems. Already at this time a CompactFlash™ card with 1GB of flash memory (see Figure 1) can be purchased commercially and IBM has sold a miniature magnetic disk in a similar package since year 2000. It is therefore

instructive to look carefully at these technology trends and try to understand their implication.

Figure 1: A commercial 1GB CompactFlash™

Figure 2, a logarithmic plot of magnetic disk storage density against year, shows that disks of a fixed physical size are roughly doubling in capacity at an annual rate [11]. Following the trend forward, by 2010 the storage density of a disk will be around 1TB per square inch, appropriate for a mobile device using a compact flash card form factor.
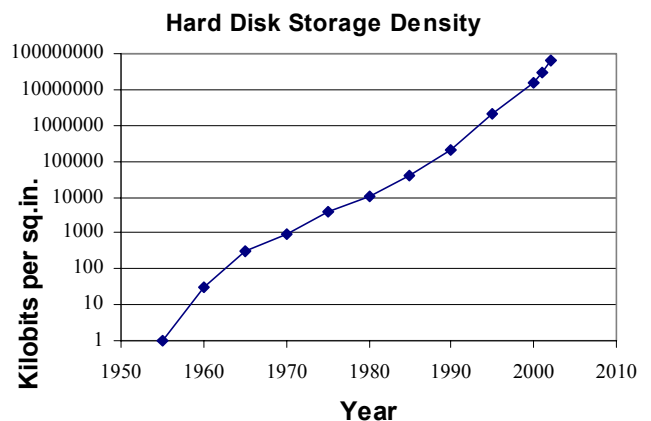

Figure 2: Storage Density (bits/sq. inch) roughly doubling annually

Communication, on the other hand, is also improving, but the trend for increased available bandwidth is less steep. Computer users have enjoyed

improvements in LAN and modem technology for 10 years, seeing broadband-to-the-home data rates of up to 1.5Mbps. For the mobile user, wide-area wireless connection speeds have increased from 19.2kbps, provided by CDPD services, to a maximum of about 100kbps service supported by General Packet Radio Service (GPRS), still a far cry from their wired counterparts. When 3G services roll out we are promised 2Mbps, but it is widely recognized that the actual bandwidth will be variable and a more typical realization will be closer to 100kbps.

An additional factor to keep in mind is that these latter services require considerable investment in infrastructure, and will not be deployed ubiquitously for sometime. Furthermore, the parent companies have spent substantial amounts of money to acquire licenses for wireless bandwidth, an investment that can only be recovered from the consumer. Therefore, these services will likely remain costly for some time.

WiFi [2] networks, on the other hand, offer reliable 11Mbps coverage but are currently only accessible as "hotspots" with unpredictable availability. However, this is a growing market and has taken the cellular companies by surprise. Today, there are signs that a grass-roots WiFi network is beginning to be created and might eventually be deployed wherever it is needed. But whatever happens, it will take time for such a network to become established and there is some uncertainty that the 802.11b standard is the one that will ultimately prevail for wireless LANs.

For these and other reasons, the trend in affordable communication improvement is therefore on a much slower track than that of storage density.

When designing a mobile device there will always be engineering tradeoffs that shape its capabilities and physical form. The resulting design compromises must in turn be based on a prioritized list agreed upon by the design team. For example, a requirement for a device to be small might be at odds with it having a long operating time: operating time is linked to battery capacity, which in turn is linked to battery size. The current state of the art for any particular technology (e.g., battery, display, processor clock, memory or type of radio) is clearly a defining limitation of a design that uses it. It is the projected improvements, and limitations, of storage density and communication that are the focus of our comparison.

This remainder of this paper discusses the implications of these trends. Section 2 is a brief historical analysis of the system design options that result from trading off communication bandwidth and storage capacity. Section 3 examines novel applications that are enabled by the exponential growth of storage and how this may fundamentally change the way we use mobile devices. In Section 4, we make some predictions for the future, and Section 5 concludes with recommendations to researchers working in this field, in terms of the relative importance of system issues that should be considered when pursuing research in ubiquitous and pervasive computer systems.

2   A spectrum of options

Historically, storage has been a major factor effecting the capabilities and design of computer systems. Early systems relied completely on local storage, while other models used communication to access remote data sources. It was not until the convergence of storage and communication that the modern day Internet took off to create computing as we know it today. Similar patterns can be seen with consumer video consumption, through technologies such as VCRs, broadcast TV, and Digital Video Recorders (DVRs). Mobile systems are starting to repeat some of the same trends as "stationary" computing; however, mobility brings unique opportunities and challenges which will require new solutions and open up new application domains.

Early PC systems were isolated islands of storage: capable of performing their self-contained tasks, but required significant amounts of manual effort to move things around. This model was adequate for spreadsheets and many personal productivity applications, but did not encompass the power of "remote" content. This scenario is equivalent to a VCR and TV without an antenna or cable – it would allow you to watch movies but not tap into the dynamic nature of "live" media. Furthermore, until recently, it has been impractical to carry all your data with you on a mobile device; however, in the last couple of years storage trends have enabled laptops and PDAs to provide for most of our immediate storage needs. In the future, increasing storage densities will enable applications such as portable media collections, to enable me to carry all of "my" movies, wherever I go.

The converse of local-storage systems are communication-centric models that allow access to remote information with a minimum of local resources. Broadcast TV and cell-phones are two popular examples of this technique – lots of available content with little or no local storage. For computers, there have been many systems that have explored computation platforms without relying on local storage capability [4, 6, 12, 13]. The problem with these communication-centric models is that they are dependent upon the remote source of information, which makes it very difficult to optimize, personalize, or sometimes just operate the system. Without a VCR, for example, you are required to watch a particular show when it's on, not when you want to watch it. The constraints of mobile devices, such as limited battery life and varying network availability, exasperate these problems and make local storage a very effective means to improve device operation.

Hybrid models, which offer both the capabilities of local storage and communication, access the best of both worlds and provide a very compelling user experience. Digital Video Recorders, such as TiVo, allow users to proactively download media content to local storage and view it whenever they want, dramatically changing their TV viewing experience. For desktop PC systems, combining local storage and the Internet allows us to efficiently manage collections of personal photographs and easily send them to friends & family. Furthermore, local storage allows for "unseen" optimizations such as local image caching which dramatically improves the web-browsing experience. Mobile devices are starting to see similar benefits from the confluence of storage and communication technologies: laptops with wireless connectivity, phones as PDAs, and emerging devices such as the Apple iPod[3], and Intel's Portable Media Player (PMP) (see Figure 3), which will enable access to dynamic media whenever and wherever we want it.

Figure 3: Intel's Portable Media Player (PMP) prototype demonstrated at CES 2003

The Personal Server [14] (see Figure 4) is an emerging research project that allows access to personal content, stored on a mobile device, through any convenient interface: accessing my address book through your laptop, for example. By breaking down the barriers between devices, the project aims to increase the utility of mobile computing and bring personalization to the environment around us.

Another focus of this project is to take advantage of localized communication technologies, such as Bluetooth [1], to avoid service provider costs, and some of the bandwidth and power limitations. In this example, a different kind of ubiquitous communication is being used, one based on local spheres of connectivity in combination with local storage to achieve the desired mobile result.

Internet Suspend Resume [5], on the other hand, enables anytime/anywhere access to a familiar computing environment by migrating a complete execution environment through the network to a local virtual machine. By relying on local storage capacity, this technique enables new forms of mobile computing that do not rely on the limited capabilities of a mobile device.

Both these projects combine storage and communication to provide unique capabilities tailored to mobile contexts. As storage capacity and density continue to increase, these models will allow ubiquitous access to content without compromising accessibility, content, or convenience.

Figure 4: Intel Research's Personal Server

3   New opportunities

When examining any capability the implications of an exponential growth trend are not entirely obvious, perhaps because most of the effects we encounter in our daily lives are usually based on linear growth. To illustrate this point we provide three examples of mobile applications that are based on the potential exhibited by exponential storage trends: looking forward to what will be available in the next 10 years as the result of exponential improvements in this technology.

Example 1: *Recording your life experiences*.

Consider a device that is capable of recording everything you have ever said in your entire life. It would allow random access to sentences you have spoken or entire conversations you have had with friends, colleagues and businessmen: archiving any particular occasion that you wish to recall. The system could even be used to record your own personal monologue – giving the phrase "talking to yourself" new meaning. Could such a device be built in a form that is small enough that it could be incorporated into a mobile platform – unobtrusive enough to be carried with you at all times?

This proposal might seem absurd, and there are indeed many reasons why such a device may not come to fruition; however, storage capacity is not one of them.

From an academic point of view, we can calculate how much storage would be needed to support this application if it had to be provided in a 1 square inch disk.

Consider the following calculations for telephone-fidelity digital audio:

- Individual lifetime to record: 80 years
- Fraction of life awake: 2/3
- Compressed audio sample rate: 16kbps .

➢ Storage capacity required: 3TB
➢ Using a projection based on Figure 2, this would be possible by 2012 in 1 sq. in.

Taking the concept further, we can repeat the calculation for video capture. The MPEG4 compression standard can provide an acceptable image stream at a few hundred kbps and support a ½ VGA resolution. Here, we use a generous sample rate of 512kbps to guarantee that images would be captured with reasonable quality.

- Individual lifetime to record: 80 years
- Fraction of life awake: 2/3
- Compressed video sample rate: 512kbps

➢ Storage capacity required: 97TB
➢ Using a projection based on Figure 2, this would be possible by 2017 in 1 sq. in.

Thus, in about a decade, it may be possible to store a lifetime of audio in a disk contained in a compact flash form factor, and only 5 years later the same could be done with digital video. In fact, this estimate is conservative because users could start with a smaller disk and simply upgrade when necessary.

There are many legal and social implications for this type of recording. We have described a box that witnesses every event in your life, recorded and perhaps digitally signed for authenticity. A tamperproof box housing the device might also provide enough assurance to the legal system that the data was in fact genuine, in which case for disputes in criminal cases the device is also a reliable alibi. However, would people be comfortable knowing their entire life was on file – subject to subpoena or other undesirable use? Either way, the *feasibility* of storage is not an issue.

The pervasive deployment of digital surveillance cameras can also benefit from the development of inexpensive bulk storage. Many cameras that usually require a constant network connection could be replaced by disconnected sentinels: the cost of deployment would be reduced and the locations where these systems could be deployed are expandable almost without limit.   To support this mode of operation, portable cameras may eventually be manufactured with enough on-board storage that everything that has been observed in the lifetime of the camera can be recorded. An on-board processor and wireless link might still be required, either to allow remote access to the data, or to send alerts notifying the detection of suspicious activity. A decade of improvements for existing processor and wireless technology, alongside the trend in storage densities, could easily enable us to build such camera sentinels in this timeframe.

Example 2: *Mobile media preloading*.

Preloading storage devices with bulk information content at the time of purchase could enable new forms of data-on-demand without requiring strong network connectivity. Data could be encrypted, accessible only when the requisite key is purchased – or added as a public service by government agencies.

Consider a conventional audio CD, which stores up to 640MB of data. In 10 years, a pocket-sized 60 TB disk could store up to a million albums, compressed – a number which is considerably larger than the available inventory of any physical music store today. Extending this example to digital video, over ten thousand DVD movies could be stored on the same disk (4.7GB per movie) – again larger than any existing movie store. Although a *wired* at-home broadband connection would probably enable us to access these movies on demand – the expense of accessing them over a mobile wireless link may still be prohibitive, in terms of time, cost, and power consumption.

Of course, there is the issue of copyright, but each piece of music could be stored in encrypted form – requiring only a small digital key to access the data. Such a purchase could be made as a simple financial transaction across a wireless link, requiring less than 2000 bits to immediately gain access to gigabytes worth of data. Storage manufacturers will continuously be searching for ways to differentiate their product in an industry that is becoming more and more commodity driven each day. Preloading storage with information provides a means to differentiate based on content, not just capacity.

Example 3: *Content caching for mobile devices*.

Data caching is a powerful technique for trading storage for bandwidth – reducing the need to download new data by remembering what has been seen before. Currently, desktop systems typically cache text and images from pages directly accessed by the user. Utilizing increased storage capacity, it would be possible to proactively cache not only the top-level web page, but also secondary web pages [8], high-resolution images (for zooming) or web applications with complete datasets. For

example, if a person is browsing for travel directions while at home using a high-bandwidth connection, they may not need the details of every turn and street corner until they're actually lost on the road. By proactively caching the details, their mobile device won't need to download any information over an expensive wireless link when on the move.

Following this line of reasoning, it would be similarly possible for specialized agents to download content just in case it might be useful. For example, if your calendar has an entry that says "Tokyo" in it, the system might just download interesting content about Tokyo – assuming you're either taking a trip there or even just thinking about it. Similarly, an agent could continuously download new content to your device, e.g., recommended new music based on your listening habits, which would then be available to you *just in case* you had some free time while on the road. (This content could be unlocked dynamically just like the preloaded media in the previous section.) By proactively transferring data while the device is connected to a host computer with a high-bandwidth serial link (perhaps while charging), the system again trades local storage for reduced communication while mobile.

One problem with cached or preloaded data is that it can't handle dynamic changes in content, but advanced optimizations can be used to minimize the amount of data to be transferred. For example, you might get caught in a heavy thunderstorm if you're relying on a long-rage forecast downloaded last week! Techniques such as the Low-Bandwidth File System [7], sends content as changes to previous versions, relying on information stored on the local device: the more data that can be stored locally, the less needs to be transferred over the wireless link. New versions of large data-sets, such as a dictionary or encyclopedia, would only have to be transmitted as small updates to existing text or a few additional entries.

4   Predictions for future mobile design

There are eventually going to be physical limits for the storage density achieved by rotating magnetic disk technology; however, storage is on a fast research track and it appears there are more physical options that can be applied to improving storage density than exist for improving communication bandwidth or processing capability. These include 3D stacking of memory elements, polymer memories, and MEMS based nano-memories.

Given the trends we have described in Section 1, and the huge potential of the examples we have provided, it is clear that massive portable storage capabilities will play a significant role in the design of mobile systems in the

future. We can expect that PDAs and cell phones will take advantage of the new storage capacity as it comes available. 1GB compact flash cards are already available, and the disk drive on the laptop used to prepare this text has a capacity of 60GB. There is little doubt in our minds that for another decade the storage trends will continue to roll out as predicted.

The last example in Section 3 introduces the notion of Proactive Computing [10], which can be an effective tool for mitigating some of the difficulties of mobile computing. Autonomous agents will be the key to moving beyond current models of pervasive computing, particularly as the number of available devices expands beyond what is reasonable for us to manage. Massive file systems enable the proactive *statistical* preparation of data: storing information in case it might be needed – mitigating a computer's inability to make accurate predictions with high-density storage.

5   Conclusion

There have been many visions of pervasive and ubiquitous computing [9, 15], and most of them have some notion of ubiquitous connectivity. For reasons outlined in the introduction, continuous high-bandwidth communication can be less appealing than commonly assumed. Local storage, however, can be a powerful tool to work around many of the apparent limitations: a large amount of local data can be easily transported and will enable many new applications. Wireless communication, therefore, will mainly be used for data that is either completely new or of a more ephemeral nature, such personal communication, financial transactions, and enabling decryption keys. Preloaded storage, or simply remembering what has been before, can be used for everything else.

Researchers in the area of pervasive computing would be prudent to take notice of these trends when designing novel systems, in order to optimize the impact of their work. Research ideas often take some time to mature into a product, a period in which communication bandwidth and memory density can take significant strides forward. Projects that are sensitive to these trends should carefully consider their system requirements in order to ensure future relevance. During this process, the relative growth factor of two competing trends, e.g., storage and communication can complicate a design, particularly when one trend is out striping another and will eventually dominate many of the design issues. Once again we emphasize that exponential trends are not always well suited to intuition and careful analysis needs to be made to consider these cases.

Finally, although we have focused on the relative capabilities of communication and storage over time, it is

worth remembering that these are just two dimensions among many that influence the design of mobile computing. In almost any dimension we can consider, including displays, processors, handwriting recognition, voice recognition, power management and energy storage, the technology improvements expected in the next decade will continue to make mobile devices, and the systems that support them, an exciting area of research.

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