COVER FEATURE

Device Ensembles

The ubiquity of wireless local and personal area networks, an expanding array of intelligent handheld devices, and an increasingly mobile lifestyle are enabling new forms of ensemble computing. Looking across four system layers—link, network, data, and application—the authors survey the technologies, standards, and leading-edge research making device ensembles a reality.

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Notebook computers, cell phones, PDAs, digital cameras, music players, handheld games, set-top boxes, camcorders, and many other consumer electronic devices have a wide range of powerful and useful capabilities. However, getting these devices to work together can be frustrating. For example, you probably have asked yourself one or more of the following questions:

- How do I get my cellular handset to share phone numbers with my notebook computer?
- How do I shuffle photos from my camera, when its memory card fills up, to my digital camcorder?
- How do I check incoming SMS messages on my game console?
- How do I network my PDA through my cell phone's GSM data channel?

In the future, these and other digital devices will work in concert, like an ensemble of musicians that achieves a total effect greater than the individual performers. Toward this end, new low-power and relatively high-bandwidth wireless technologies such as Bluetooth and ultrawideband are poised to replace infrared for communication. At the same time, the computer and consumer electronics industries are defining interoperability standards around "digital living."

Nevertheless, creating ensemble capabilities remains elusive for computing devices, which in many ways are further from this ideal than cordless power tools; a hammer-drill, floodlight, nail gun, and circular saw can at least share battery packs.

Some claim that all personal devices will disappear except for full-featured cell phones, which already have integrated cameras, PDAs, Global Positioning System (GPS) tracking, and music players. In a future with one device, is ensemble computing a red herring? Don Norman, the respected usability researcher, likens such a megafunction device to a Swiss Army knife: "When one machine does everything, it in some sense does nothing especially well, although its complexity increases."[1]

People will always be motivated to build and use tools that feel natural. Although some capabilities will merge into adjacent form factors, like personal information management (PIM) merging into cell phones, other capability/form-factor combinations will find a steady state. We will continue to add new special-purpose devices to our digital tool chest, and, as Figure 1 shows, hope that all these tools will work well together.

Although the idea of pairing devices for enhanced capability is not new, we believe the industry is at an "ensemble inflection point" due to the ubiquity of wireless local and personal area networks, the expanding array of intelligent consumer electronics devices with embedded IP technology, and an increasingly mobile lifestyle. We look across system layers, from communication to application, to survey the technologies, standards, and leading-edge research that is bringing people closer to everyday ensemble computing.

USAGE MODELS

Early usage models for ensemble computing cen-

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tered on data synchronization between desktops and personal digital assistants. With the advent of smart phones and wireless PDAs, data synchronization became more transparent—for example, Research in Motion's BlackBerry 7230 synchronizes calendar entries using the General Packet Radio Service (GPRS), and many cell phones support Bluetooth synchronization.

Bluetooth wireless networking has also driven a range of new usage models. Saab, BMW, and other automakers use Bluetooth connectivity to provide a hands- and eyes-free way for drivers to make and receive cell phone calls. These systems pair the car's speaker, microphone, and steering wheel audio controls with the driver's cell phone, which could be in a briefcase in the back seat or a gym bag in the trunk. Future cell phones will also be able to share the vehicle's display systems.

Increasingly, people are using digital devices other than the familiar desktop computer, laptop, and cell phone. The Digital Living Network Alliance (www.dlna.org) is a consortium formed by the PC, mobile, and computer electronics industries to improve interoperability among home media devices. Specifically, the DLNA is exploring how media servers—advanced set-top boxes, digital video recorders, and so on—can interoperate with media players such as TV monitors, stereo and home theaters, and PDAs.

The DLNA is providing guidelines in the areas of connectivity and networking, device discovery, remote control, media management, media format profiles, and media transport. Driving version 1.0 is a local user interface on a media player for finding and selecting content to play from a media server—for example, a digital TV pulling content from a PC for viewing. Future versions will include use cases for pushing data to players as well as remote control of servers and players.

The DLNA is making progress in a few important ensemble usage scenarios for digital media in the home. However, as the "What We Carry" sidebar illustrates, device ensemble capabilities have a long way to go to address people's daily needs.

Device interoperability applies to many system levels. With respect to ensemble computing abilities, industry and research are focusing on the following four layers to enable numerous top-to-bottom capabilities:

- *link layer*—for example, to enable low-power, short-range communication;
- *network layer*—for example, to route IP through the "best connected" device;
- *data layer*—for example, to share and sync addresses, photos, and other media; and
- *application layer*—for example, to create applications that span multiple devices, such as an e-mail program on a PDA and notebook computer connected to the same underlying server data.

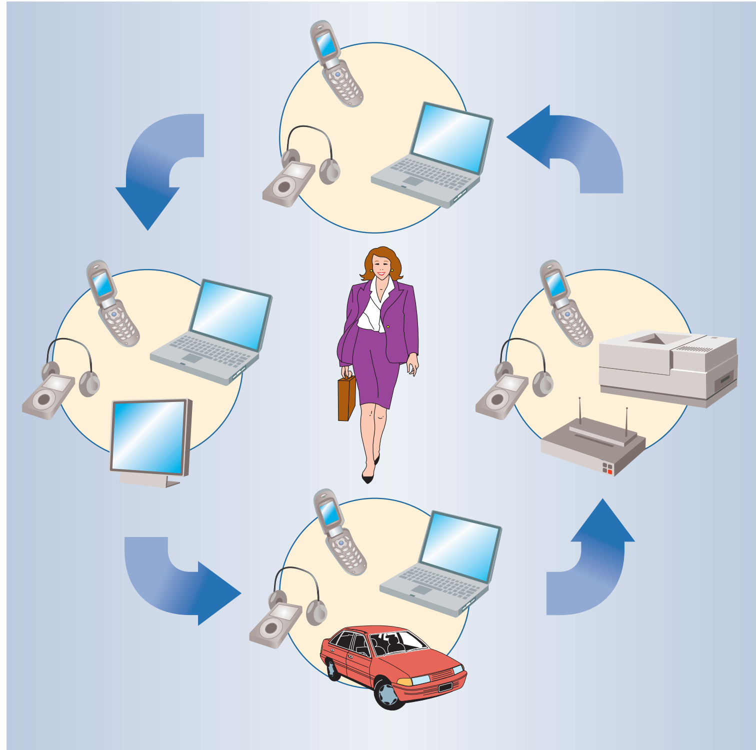

Figure 1. Ensembles of digital devices are emerging for common usage models—at home, at work, and on the road.

One purpose of these layers, as is the case with the International Organization for Standardization's Open Systems Interconnection seven-layer reference model, is to clearly define capabilities that can improve ensemble interoperability between computer and consumer electronics manufacturers.

LINK LAYER

Ensemble computing spans both local area networks (LANs) and personal area networks (PANs) with desired link-layer properties including low power, medium to high bandwidth, and always-on connectivity.

Ubiquitous technologies

Two communication technologies that have become ubiquitous in many fixed and mobile devices are infrared and Universal Serial Bus.

IrDA. In 1994, the Infrared Data Association (www.irda.org) released the first specification for low-level protocols for wirelessly transferring data via infrared radiation.[2] IrDA-equipped devices can communicate at short range (1-2 meters), have a line-of-sight (LoS) requirement (which some believe is better for security), and support data rates between 4 and 16 Mbps.

What We Carry

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To better understand the future of technology, we recently conducted a study of "technosocial" device ensembles and usage models in Los Angeles, Seattle, and London. Our goal was to gather empirical data on what devices people between the ages of 23 and 33 carry with them outside the home and office and what they try to accomplish using these technologies. Our research methodology included contextual interviews, diaries, shadowing, and photo elicitation.

Things We Use

We began with a simple question: What do people carry? Primary objects that people routinely carry include cell phones, laptops, wallets, MP3 players, and reading material. Each of these objects enhances the way people represent themselves. As Annabelle, a commercial producer in London, said, "My things are totally me, and I'm totally my things."

Mobile phones are social devices that connect individuals with one another, whether through a voice call, text message, or e-mail. A laptop typically represents a person's profession: It's where most work happens. A wallet's contents provide a sense of self-worth—for example, what and how many credit cards we have, and the amount of cash we feel comfortable carrying. An MP3 player communicates personal tastes and aesthetics. A Palm device or Filofax organizer serves as an archive of an individual's daily events—a sound-byte journal.

Together these objects provide an intentional interface to various communications, financial, entertainment, and transportation infrastructures.

Macro/micro changes

The devices people carry are dynamic, varying across both macro and micro time scales.

Many participants in our study had added or removed mobile technologies within the past six months. This change typically accompanied a life event that significantly altered their personal identity or social relationships—for example, getting a new job, breaking up with a significant other, or moving to a different city.

Other changes occur more frequently. Research subjects had daily routines—going to the office, working out at the gym, going to a friend's home, and so on—that necessitated transporting a different inventory of devices. Many expressed the importance of "just having the right amount with you." For example, Thomas, a London-based business developer, carried his iPod on gym days, but used his Sony Walkman while jogging. Katie, a freelance animator also based in London, constantly had to repack what she took with her daily depending on whether she was working alone or which client she was meeting with that day.

Technology should allow the migration of information and identity along finely tuned variables, particularly in the case of portable devices that are both closely tied to personal identity and frequently upgraded to different service providers and manufacturers.

All tangled up

Sitting inside a coffee shop on Melrose Avenue in Los Angeles, Brad, an aspiring screenwriter, expressed a desire for simple-to-

The IrDA initially left the upper layers to individual vendors, but the lack of a complete set of standards exasperated users looking for devices from different manufacturers to work together for specific tasks, such as exchanging digital business cards. The IrDA has since defined protocols for different usage models, called *profiles,* including using infrared to connect to LANs, sending documents to printers, exchanging calendar items and business cards, downloading images from digital cameras, and vending payment, among others.

Although IrDA currently is available on various notebook computers, PDAs, and printers, many believe the early lack of usage model interoperability has hindered user adoption. This lesson was not lost on the Bluetooth Special Interest Group, which rapidly defined more than a dozen interoperability profiles.

USB. Universal Serial Bus is a wireline expansion bus technology first developed in 1995 with the goal of making connecting a peripheral to a PC as easy as hooking up a telephone to a wall jack. Associated plug-and-play software on the host side recognizes hot-plugged devices and loads the appropriate software drivers, generally providing a much better user experience than the prior serial connection.

Today, USB is a tremendous market success, with most peripheral vendors adopting USB and all new PCs shipping with USB ports, some with the newer high-speed 480-Mbps USB. This success is extending to mobile devices such as phones and cameras through USB On-the-Go, a revision that defines a small form-factor connector and low-power standard. Another advantage for mobile devices is the ability to charge batteries directly off the USB connection.

FireWire. A sister technology to USB, IEEE 1394, better known as FireWire, can be used to connect up to 63 external devices. In addition, it supports plug-and-play and hot plugging, and provides power to peripheral devices.

Current technologies

Bluetooth and Wi-Fi are two wireless communication technologies that have become increasingly popular in recent years.

Bluetooth. Many consider Bluetooth to be the successor to IrDA, as it provides host-to-host communication as well as USB-like capability enabling the use of wireless keyboards, mice, telephone headsets, and other peripherals. In 1998, IBM, Intel, Nokia, Toshiba, and Ericsson formed the use technology that works together. "My dream," he said, "is for a wrist-mounted unit with GPS, a PDA, a cell phone, an MP3 player, and a grappling hook connected to a Bluetooth earpiece that can be toggled between music and cell phone."

Indeed, participants universally wanted to remove the clutter associated with the technology they carried. For example, Thomas and Lili, a media producer in LA, observed that their laptops had their "own bags" containing coax cable, modem cords, USB drives, extra batteries, CDs, power bricks, headset wires, and even a "portable" scanner—in short, the laptops required a lot of stuff to work.

Laptops aren't the only culprits. On one Friday afternoon in LA, colleagues urged Salina, a recruiter, to "unplug" her iPod and share her music with the office. Although she managed to set up Air Tunes to play through the office stereo, Salina hadn't charged the device in some time, and the music stopped an hour and a half later. "I just can't carry everything with me all the time," she explained. "It's just too much stuff!" Even a "simple" technology requires lots of supporting devices to work.

However, technology offered some hope to participants as well. One of the benefits of Wi-Fi was that it made life simpler, despite some complaints about setting it up. Ensembles that provide simple functionality, engagement, and connectivity show great promise for meeting people's daily needs.

Playing nicely together

If supporting a technology requires effort, getting devices and information to work together is a further problem. For example, Atom, a video producer in LA, carries his laptop, camera, iPod, and mobile phone with him at all times. Whenever he gets out of his car, Atom joked, he "pats himself down" to make sure he has everything with him.

For his home entertainment needs, Atom complained of the difficulties of syncing his iPod not just with his laptop but also with his wife's laptop and iPod. He also struggles with moving various audio, video, and photo work files around. Atom is often on site scouting or filming, and his laptop has no direct access to his work desktop machine or the Avid video decks. He therefore must move all his large files to the other stationary machines at work via his iPod.

Coordinating information isn't just an archiving problem—it's a practical one that occurs in real time. For example, Kelly, a marketing director in London, received a call from her husband, who wanted her cousin's phone number to check on a wedding present. He didn't have the number on his phone; it was on Kelly's phone, but she couldn't get to the number while talking. She hung up, dug her Filofax out of her bag, and wrote the number down on a scratch page. She then called her husband back with the number. This was the most common problem we observed, and one that frustrated several participants.

Devices themselves also cause disruption. For example, while listening to music on his iPod on the ferry between Bainbridge Island and Seattle, Jason, a software developer, placed his mobile phone on the table along with his coffee, laptop, and various papers. When the phone began vibrating, he didn't have time to check caller ID, pop out his earplugs, and answer the phone. Jason

Bluetooth SIG (www.bluetooth.com) with a vision to unify the computing and telecommunications world. The resulting Bluetooth standard operates in the 2.4-GHz frequency band and supports real-time data with rates of 1 Mbps and a range of 10 to 100 meters.

Unlike IrDA, Bluetooth has no LoS restriction, goes through walls, and supports point-to-multipoint and ad hoc wireless connections. On the downside, although the Bluetooth protocol discovers other devices, the user must distinguish between multiple devices within range; in contrast, IrDA users can simply point two PDAs at each other and push a button.

Wi-Fi. Another wireless technology that has gained tremendous popularity is IEEE 802.11, or Wi-Fi, which currently encompasses four specifications: 802.11, 802.11a, 802.11b, and 802.11g. These standards support data rates between 1 Mbps and 54 Mbps and two operation modes. When communicating with an access point that is connected to a wired LAN, a client is said to operate in *infrastructure* mode; alternatively, and much less commonly, clients can act in a peer-to-peer *ad hoc* mode that is desirable for device ensembles.

Wi-Fi uses more power than Bluetooth but provides a longer range (18 to 500 meters depending on conditions and bandwidth), higher data rates, and more energy-efficient bulk data transfers. Like Bluetooth, it supports PANs as well as wireless LANs. In-Stat/MDR predicts that the market for embedded Wi-Fi clients will reach 226 million units shipped in 2008.[3]

Emerging technologies

Several emerging wireless technologies claim to offer the best of both worlds: low power as well as high bandwidth.

UWB. Often touted as a replacement for Bluetooth, ultrawideband offers much higher data speeds—currently 40 to 60 Mbps, and eventually up to 1 Gbps. Unlike conventional radio transmitters, UWB broadcasts at very low power over an extremely wide band of frequencies.

Competing industry factions are promoting two different UWB approaches: direct-sequence ultrawideband and multiband orthogonal frequency-division multiplexing. The IEEE 802.15.3 Committee is tasked with developing one ultrawideband PAN standard, but it has been unable to converge on DS-UWB or MB-OFDM since neither side has been able to garner the necessary 75 percent support.

observed that there was no smooth, seamless way for him to coordinate all his devices, a sentiment echoed by other participants.

Usage Models

Beyond exploring the relationships among devices, we have captured some key usage models. These models focus on users rather than the technologies—that is, what people try to accomplish with the things they carry.

Competing for attention

As communication technology becomes pervasive, people within our personal network increasingly fight for our attention. Resolving these conflicting demands is no easy task. The participants in our study preferred certain channels of communication but also recognized the need to deal with friends, family members, or colleagues in appropriate ways.

To be a good communicator, you must understand the people you talk with as well as the social context. Are they at work, at home, or on the road? Do they prefer texting, e-mail, or conversation?

Sandy, a full-time surfer and part-time clothing designer in LA, said, "All my communication is branded, it has to be. What I use and how I use it define me. It's life in LA.... My e-mail takes time to do because it has to fit my brand. People save those e-mails. They save that 'image' of me."

New mobile technologies help us to maintain our social networks. Atom, who frequently coordinates with bands, noticed a shift in the past two years from mobile phone use to short message service, instant messaging, and e-mail. "Seems like everyone I work with in a band now uses a Sidekick. If you call, they never answer or return your call. The only way to get through is to get them on their Sidekicks."

Once single-channel communicators, we now rely on multiple channels. Our subjects continually shifted from one technology to another: texting to IM, IM to e-mail, e-mail to mobile phone, and so on. Sometimes they used two or more simultaneously—for example, reading text messages from one person while speaking with another via cell phone. In other cases, they switched modes due to the context of communication—for example, the person they were trying to reach couldn't talk but could respond through text messages.

Personal portable devices create other demands on our attention. For example, satisfying their power demands is a persistent problem. Brad waited half an hour to get a table close to a power outlet in the coffee shop. For the same reason, Jason was one of the first in line at the ferry in the morning. Annabelle searched a shoot site to find an available outlet for her phone. Power supply to the laptop continues to be a gate-keeping function, creating a new breed of power vampires searching the environment.

Striking a balance

A consistent pattern we observed in our study was that devices spanned many contexts of use, both in combination with other devices—as in the case of a mobile phone, PDA, and computer—and in fluid situations such as moving from work to play mode and back again. As these boundaries blur, people develop alter-

ZigBee. Another radio technology gaining a following in the sensor networks community is ZigBee (www.zigbee.org), which operates in the worldwide unlicensed bands including 2.4 GHz (global), 915 MHz (Americas), and 868 MHz (Europe). At those bandwidths, ZigBee can achieve raw data throughput rates of 250 Kbps (10 channels), 40 Kbps (6 channels), and 20 Kbps (1 channel), respectively. Transmission distance is expected to range from about 30 to 245 feet, depending on power output and environmental characteristics.

NFC. Recently, the Near Field Communication Forum (www.nfc-forum.org) proposed using radio-frequency-identification-based technology to help users interact with and exchange small amounts of data with devices in the immediate environment. With NFC-enabled devices, "you will make your travel reservations on your PC and download your tickets to your mobile phone or PDA, just by bringing it next to the computer, then you will check in for your trip by touching your handheld device to the departure gate kiosk—no paper, no printing needed."

Because NFC has a range of a few inches, the user can easily manage data exchange and device association (pairing), making this a complementary mechanism to Wi-Fi, Bluetooth, or UWB that effectively returns the control present in IrDA's LoS communication. The NFC interaction model of touching devices to each other—using a near-field link-layer mechanism followed by network-layer pairing, potentially through a different link layer—seems practical and promising for user-mediated ensemble formation.

NETWORK LAYER

Device discovery, association, and ensemble formation are challenging obstacles today. The first step in eliminating these barriers is to make the user experience simple, secure, and intuitive. This is accomplished at the network layer along with routing and controlling information flow among hosts.

The key capabilities to ensure formation and communication among ensemble devices at the network layer include

- automatic presence announcement and discovery of devices in the "neighborhood,"
- ability to query other devices' capabilities,
- easy plug-and-play-like addition of new devices, and
- self-organizing network routes.

nate methods for coordinating devices and managing data to match their need for access as well as differentiation.

Participants in our study used multiple portable devices to help manage the boundaries between work and home—particularly important to our cohort—or between different personal relationships. Some identified their laptop as a work device and their handheld as an emergency or personal communication device, in some cases keeping them in separate bags.

Although maintaining multiple devices and accounts incurs overhead in time and money, the persistence of this practice indicates a deep-seated need for bounding identity and function. Participants varied in how they separated work and personal data, but each drew explicit distinctions.

Portable devices also serve as personal islands of functionality. Our subjects used their iPods not only for playing music at work but also for storing private data such as resumes, contact lists, and projects important to them. "You never know what's going to happen," Lili said. "I like to keep my stuff with me all the time."

"Cocooning"

People use portable devices to carve out personal "cocoons" while navigating urban spaces. "When I have my earplugs in," Lili explained, "people usually get the idea that I don't want to be bothered."

After leaving his office in London, Thomas took out his iPod, adjusted the earset, and headed for the Bank Street Tube station. When his subway arrived, Thomas slid into a seat, spread a copy of *National Geographic* on his lap, and for the next 45 minutes shut out the sights, sounds, and people around him.

Mobile devices can be used to create private pockets within institutional as well as public settings. Heather, a marketer in London, was surprised how often she used her personal cell phone and Filofax at work to "take me out of this place." Likewise, Salina frequently played music on her iPod in the office to create a personal space.

Familiar technosocial ensembles such as the PC workspace and home entertainment center are fairly generic and location based. These are rapidly giving way to personalized mobile ensembles that rely heavily on portable devices and a user-centric model of communication and media engagement. ■

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A number of coordination frameworks have recently emerged that provide some of these capabilities. The ultimate aim of these architectures is to enable simple, seamless, and scalable device interoperability. It is clear that any workable coordination framework must introduce some standards into the devices' operations. The challenge is to strike a balance between standardization requirements and device autonomy.

Jini

Sun Microsystems' Jini (wwws.sun.com/software/jini) is a coordination framework that grew out of tuple-space research adapted to Java. A Jini *federation* denotes a collection of autonomous cooperating devices. The framework includes lookup services to maintain dynamic information about available devices. For describing capabilities, a federation uses registration information with attribute/value pairs.

Before plugging a device into a federation, you must configure it with an IP address, a subnet mask, and an optional gateway and Domain Name System (DNS) server. Jini uses security mechanisms native to Java; for network transports, it uses TCP/IP as well as proxies to other transports.

UPnP

Universal Plug and Play (www.upnp.org) is a framework driven by Microsoft, Intel, and other industry leaders that, as the name implies, provides a kind of over-the-network plug-and-play capability. UPnP primarily defines interoperability standards around existing lower-layer network protocols—such as IP, UDP, TCP, and HTTP—rather than at the application layer.

With an agreed discovery bootstrapping protocol, UPnP allows devices to build their own APIs to implement application-layer protocols. With the special Simple Service Discovery Protocol, devices can announce their presence to the network—with or without a directory server—as well as discover available devices. For self-configuration, UPnP automatically assigns IP addresses and DNS names to devices, using either a Dynamic Host Configuration Protocol server or IP addresses from a reserved range.

UPnP is becoming the leading choice over competitors such as zero-configuration networking, also known as Rendezvous (http://developer.apple.com/macosx/rendezvous), with the DLNA incorporating it into standards and Windows XP shipping with a UPnP stack.

Usage models for data synchronization continue to evolve.

PMG

Like typical ad hoc networks, device ensembles form spontaneously when the devices (nodes) come within range of one another, and they do not rely on network infrastructure. In an ideal ensemble, communication among nodes can flow through one or more links to reach a destination—for example, from a notebook computer over Bluetooth to a cell phone, then to the Internet via GPRS. In the course of a user's daily activities, different devices will join and leave the ensemble, the ensemble will connect to different back-end networks, and routes to those networks through ensemble devices will change.

Toward this end, some mobile devices now feature a *personal mobile gateway* that can bridge two or more wide area/local area/personal area networks. PMG capability will likely be integrated into cell phones or laptops rather than evolve into a special-purpose device of its own.

DATA LAYER

The vision of being able to use any device to pluck digital content from a personal information "cloud" is appealing. However, in reality, contact records become fragmented across devices, music is not necessarily available on the device at hand, photos cannot easily be sent to a nearby TV, and program state, such as an in-process e-mail message, does not follow us as we move from a laptop to a PDA. Interoperability across the data layer is essential for many user-facing capabilities including data synchronization, transfer, and formats.

Data synchronization

Since the appearance in 1996 of Palm Computing's Palm Pilot 1000, with its advertised capability of "easily exchanging PIM data with your PC," users have sought an efficient and reliable way to synchronize mobile devices with desktop or server computers as well as other mobile devices.

FastSync/SlowSync. Palm's early FastSync protocol associates a status flag with each inserted, deleted, or modified record. During synchronization, the handheld (and desktop) sends only those records with the status flag set. After synchronization, both sides clear the flag on all records. However, FastSync only downloads modified data; if the handheld is trying to synchronize with a new computer, it must first download the entire application's database to the system via the SlowSync protocol.

OMA. Modern data synchronization systems support wireless update and avoid SlowSync overhead by employing a central server architecture through which multiple devices coordinate. Apple Computer's iSync (www.apple.com/isync), Microsoft's ActiveSync (www.microsoft.com/windowsmobile/downloads/activesync37.mspx), and Intellisync (formerly Pumatech; www.intellisync.com) all support this configuration. The Exchange Server's ActiveSync addition uses over-the-air notification to tell client smart phones to initiate synchronization to access new e-mail messages.

To reconcile these and other synchronization systems battling for market supremacy, the Open Mobile Alliance (www.openmobilealliance.org) is promoting the SyncML standard with the backing of numerous industry players, including Nokia, Siemens, Motorola, Ericsson, IBM, Openwave, and Symbian.

P2P synchronization. Researchers are also investigating peer-to-peer synchronization among the many devices that people carry and encounter throughout their day and that can intermittently connect to one another. Maya Rodrig and Anthony LaMarca[4] developed Oasis to manage read/write consistency across both mobile and stationary devices that are not always in radio contact. Oasis applies David Gifford's classic data management scheme to give more voting "weight" to frequently used devices that receive more write updates. The result is strong consistency as well as high data availability in partially connected environments.

Footloose is another P2P "sneakernet" approach by Justin Paluska and colleagues[5] that sends information through communication links formed by devices that come close to each other. However, instead of locking data, Footloose uses optimistic writes and sends potentially conflicting data through the network of devices. It achieves eventual consistency by applying conflict resolution in applications on certain devices.

Internet Suspend/Resume. Usage models for data synchronization continue to evolve. Michael Kozuch and associates propose Internet Suspend/Resume,[6] a technology that lets a user suspend work at one machine and resume it on another, mimicking the opening and closing of a laptop. ISR layers virtual machine technology on a distributed file system that moves change deltas over the wire. In the future, this mechanism could address P2P synchronization by rapidly transporting complete system state across devices as users interact with them.

Data transfer

A second data-layer capability that researchers are exploring is transferring data when needed rather than synchronizing it across devices. This approach includes many DLNA usage models such as sending photos to a TV and streaming music to wireless speakers. One possibility is to create a common name space for all of a user's storage. Edmund Nightingale and Jason Flinn's BlueFS[7] is a distributed file system for pervasive computing that gives access to any piece of data anywhere by tracking it down across multiple computers.

Randolph Wang and colleagues[8] have developed Segank, a prototype distributed mobile storage system that can track data by first checking local storage, then nearby devices via Bluetooth, then the local network with Wi-Fi, and finally wide-area resources through the Internet. The team ultimately hopes to shrink the device to wristwatch size.

Data formats

In many situations, synchronizing or transferring data involves not only copying from one device to another but also translating the data into the appropriate format. Intellisync, for example, converts PIM data between dozens of program formats. Likewise, the DLNA is paying great attention to data formats, especially how audio or video sent to PDA devices often requires conversion or transcoding.

Media is very dependent on hardware characteristics such as color depth, display size, and video rendering. Data translation between PIM applications might become passé in the event of widespread adoption of a PIM standard or use of self-describing XML. However, as long as mobile devices have different form factors, transcoding for hardware variations will be necessary for ensemble interoperability.

APPLICATION LAYER

The application layer provides ensemble end-user services. For example, devices can act as user interface peripherals for one another: A TV might turn into a display for a camera's photo show, or a laptop's keyboard might turn into a text-entry device for a cell phone. With the help of Java 2 Micro Edition, user groups are experimenting with many ensemble user interface capabilities, such as the Clicker application that converts a Sony Ericsson phone into a remote mouse.

Beyond using devices as interface "interactors" is the ability to use whatever device is at hand as a window into one application. Multidevice applications can be extremely engaging. For example, when reading e-mail, our colleagues at Intel regularly move back and forth from their notebook computer to BlackBerry devices. Although the e-mail programs are different on each device, they share basic functionality and, most importantly, a common mail server. This gives the impression of operating a single program from different devices.

The shift toward an ensemble interaction style has occurred with as yet little support from device manufacturers.

Designing applications with multimodal and multidevice capabilities is the goal of Anoop Sinha's CrossWeaver system.[9] This tool lets designers sketch interface ideas for multiple devices and then turn these ideas into working prototypes that run across multiple standalone devices processing multimodal input. The tool also captures detailed traces of user input, which enables designers to refine their interfaces across devices.

Designing applications for multiple devices is more time-consuming and difficult than designing them for a single device. Multidevice user interfaces will remain a rich field of study as researchers explore the tensions between automatic and manual techniques.

During the past few years, the personal computing ecosystem has evolved by leaps and bounds. Today it is not uncommon for a college student to carry a laptop, cell phone, and MP3 player—and perhaps a game console, media player, GPS receiver, or Bluetooth headset as well. With this growing selection, functional boundaries are blurring. People are rapidly moving between devices, using the most appropriate one available for a task and often using more than one device in the course of an activity.

This shift toward an ensemble interaction style has occurred with as yet little support from device manufacturers. However, industry groups are stepping in to reduce the burden and define new ensemble experiences. Initially, this involves simply choosing among many existing standards for different types of interoperability. The DLNA in particular is making progress in a few important ensemble usage scenarios for digital media in the home. However, it is likely that technologies such as UWB, NFC, and UPnP as well as new business models will enable more device ensembles as research results shift into products and usage models are clarified.

In the future, people will form functional ensembles not only with their own digital devices but also with others they encounter throughout the day such as thermostats, light controls, and audiovisual equipment. We believe that the numerous advantages of ensemble computing—including better data availability, improved connectivity, and cross-device applications—will lead to the development of communication and computing technologies that transform how we interact with our world and one another.

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References

1. J. Rheinfrank, "A Conversation with Don Norman," *ACM Interactions,* vol. 2, no. 2, 1995, pp. 47-55.
2. G. Vrana, "Untangling IrDA and Bluetooth," *EDN Magazine,* 27 Sept. 2001, pp. 57-62.
3. M. Singer, "Wi-Fi Adapters Turn Inward," *Wi-Fi Planet,* 24 Aug. 2004; www.wi-fiplanet.com/news/article.php/3399131.
4. M. Rodrig and A. LaMarca, "Decentralized Weighted Voting for P2P Data Management," *Proc. 3rd ACM Int'l Workshop Data Engineering for Wireless and Mobile Access* (MobiDE 03), ACM Press, 2003, pp. 85-92.
5. J.M. Paluska et al., "Footloose: A Case for Physical Eventual Consistency and Selective Conflict Resolution," *Proc. 5th IEEE Workshop Mobile Computing Systems and Applications* (WMCSA 03), IEEE CS Press, 2003, pp. 170-180.
6. M. Kozuch et al., "Seamless Mobile Computing on Fixed Infrastructure," *Computer,* July 2004, pp. 65-72.
7. E.B. Nightingale and J. Flinn, "Energy-Efficiency and Storage Flexibility in the Blue File System," to appear in *Proc. 6th Symp. Operating Systems Design and Implementation* (OSDI 04), Usenix Assoc., 2004.
8. S. Sobti et al., "Segank: A Distributed Mobile Storage System," *Proc. 3rd Usenix Conf. File and Storage Technologies* (FAST 04), Usenix Assoc., 2004, pp. 239-252.
9. A.K. Sinha, *Informally Prototyping Multimodal, Multidevice User Interfaces*, doctoral dissertation, Dept. Electrical Engineering and Computer Sciences, Univ. of California, Berkeley, 2003.

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