Energy Efficiency of Handheld Computer Interfaces: Limits, Characterization and Practice *

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Abstract

Energy efficiency has become a critical issue for battery-driven computers. Significant work has been devoted to improving it through better software and hardware. However, the human factors and user interfaces have often been ignored. Realizing their extreme importance, we devote this work to a comprehensive treatment of their role in determining and improving energy efficiency. We analyze the minimal energy requirements and overheads imposed by known human sensory/speed limits. We then characterize energy efficiency for state-of-the-art interfaces available on two commercial handheld computers. Based on the characterization, we offer a comparative study for them.

Even with a perfect user interface, computers will still spend most of their time and energy waiting for user responses due to an increasingly large speed gap between users and computers in their interactions. Such a speed gap leads to a bottleneck in system energy efficiency. We propose a low-power low-cost cache device, to which the host computer can outsource simple tasks, as an interface solution to overcome the bottleneck. We discuss the design and prototype implementation of a low-power wireless wrist-watch for use as a cache device for interfacing.

With this work, we wish to engender more interest in the mobile system design community in investigating the impact of user interfaces on system energy efficiency and to harvest the opportunities thus exposed.

I. Introduction

Energy consumption is a critical concern for battery-driven mobile devices, such as handhelds, laptops, and cell-phones. Most handheld computers serve their users directly through human-computer interaction, and most tasks are interactive. From the user's perspective, the concern is not really the power consumption itself but what the user can do, given the battery lifetime. Energy efficiency is, therefore, better evaluated in terms of energy consumption per user task. At a higher level, one needs to evaluate:

$$\frac{\text{User productivity}}{\text{Average power consumption}}$$

or (User productivity) $\times$ (Power efficiency).

From such a perspective, human factors and user interfaces have a large impact on system energy efficiency, simply because they determine not only the power consumption for interaction but also user productivity. Most low-power research has focused on reducing power consumption, given a computation or interactive task. However, it is equally, if not more, important to optimize the interaction itself, *i.e.*, reduce the interaction power and improve user productivity.

In this paper, we focus on the impact of human factors and user interfaces on energy efficiency. To the best of our knowledge, this is the first work of this nature. We first present theoretical studies of the minimal energy/power requirements for user interfaces based on human sensory limits, and then take into account the human speed for human-computer interaction. We then investigate the energy efficiency of the state-of-the-art interfaces by characterizing different interfacing technologies available on two commercial handheld computers. Based on the characterization, we offer a comparative study of energy efficiency of these different interfacing methods. We find that speech-based input has a great potential to become the most energy-efficient interfacing method since we can speak at a much higher rate than we can write or type. Such a comparative study offers guidelines for mobile system designers when choosing interfacing technologies.

As the characterization clearly shows, energy requirements of state-of-the-art interfaces are far from the theoretical minimal. In fact, interfacing components, such as the display and speaker subsystems, are among the most power-consuming components. On the other hand, human capacity is essentially limited, and the computer usually spends most of its time waiting for the human user during interaction. Therefore, significant energy is spent in waiting due to power-hungry interfacing components and a slow user, leading to an energy efficiency bottleneck. Such a bottleneck cannot be removed with more sophisticated user interfaces, which usually

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consume even more power. Motivated by memory-cache theory, we show how a low-power interface cache device with much simpler and lower power interfaces can be used to handle simple interactive tasks outsourced from a host computer, and thus improve the battery lifetime of the latter. It saves energy essentially by bringing the interface energy requirements closer to the theoretical minimal without sacrificing user productivity much for the simple outsourced tasks. In this work, we designed and prototyped a wireless wrist-watch as an interface cache device to serve an HP iPAQ handheld computer.

The paper is organized as follows. We discuss limits on energy efficiency imposed by human factors in Section II. We then offer user interface energy characterization and comparative studies in Sections III and IV, respectively. We present the design and experimental results for the wrist-watch as an interface cache device in Section V. We discuss related works in Section VI, and conclude in Section VII. It is worth mentioning that there are many other issues involved in user interface design and evaluation than energy efficiency, such as user acceptance and form factors. In this work, however, we focus on energy efficiency from a computer engineering perspective.

II. Limits due to Human Factors

This section examines how human factors impose limits on energy efficiency with regard to interfacing power and user productivity (speed). It highlights the importance of human factors and interfaces in determining system energy efficiency as compared to computing. It also provides theoretical foundations for improving user interfaces for better energy efficiency.

A. Sensory Perception-based Limits

Landauer [23] showed that the theoretical lower bound for energy consumption of an irreversible logic operation is $kTln2$, where k is the Boltzmann constant and T is the temperature. kT is of the order of $10^{-21}J$ at room temperature. All commercially available computing devices use irreversible logic operations and are hence governed by this bound. On the other hand, the computer has to communicate with its human user through the latter's sensory channels. These channels in fact set the minimal power/energy requirements for the computer output.

1) Visual output: Human vision energy thresholds have been measured in different forms [4] in terms of minimal absolute energy, minimal radiant flux, and just-perceptible luminance. Minimal absolute energy is measured for a very small solid-angle field, $e.g.$, a point source, presented for a very short time ($10^{-3}s$) so that no temporal summation of radiant flux occurs. Minimal radiant flux is measured for a very small solid-angle field lasting for a long time so that temporal summation of radian flux occurs. Just-perceptible luminance is measured for a large-area visual field. These thresholds are used to estimate the energy/power dissipation lower bound for displaying information as follows.

Minimal absolute energy: Let us assume the user's cornea area is A, viewing distance D, and viewing angle Ω. We assume the light irradiance is the same for every point within the viewing angle that is at the same distance from the point source. Let $E_{min}(\lambda)$ denote the minimal light energy reaching the cornea that is detectable by the user for light of wavelength λ. The total energy emitted by the source is thus:

$$E(\lambda) = \frac{\Omega D^2}{A_i}\cdot E_{min}(\lambda) \approx \frac{\Omega D^2}{A}\cdot E_{min}(\lambda)$$

where A_i is the area of the viewing sphere that is incident on the cornea. A_i is approximated as the cornea area A.

Experimental results reported by psychology researchers [4] indicate that E_{min} for light of wavelength $510nm$ is about $2\cdot10^{-17}\sim6\cdot10^{-17}J$. Assuming $A = 0.5cm^2$, $D = 0.3m$, and $\Omega = 0.125\cdot2\pi\ sr$, we have $E\approx3\cdot10^{-14}\sim9\cdot10^{-14}J$, which is about seven orders of magnitude larger than the energy required for an irreversible logic operation.

Note that the energy limit derived above is for rod vision, which is human vision under extremely low luminance and colorless. Only the cone vision contains color and is normally required for human-computer interaction. The energy threshold for cone vision for $\lambda = 510nm$ is more than 100 times that of rod vision. For users to sense color, the minimal energy would thus be of the order of $10^{-11}J$.

Minimal radiant flux: Let $R_{min}(\lambda)$ denote the minimal radiant flux for light of wavelength λ that humans can sense. For the viewing distance D and viewing angle Ω, the source radiant power is given by:

$$\Phi_{min}(\lambda) = \frac{R_{min}(\lambda)\cdot\Omega D^2}{683\cdot V(\lambda)}$$

where $V(\lambda)$ is the relative visibility factor and 683 is the spectral efficiency for $\lambda = 550nm$ in $lumen/W$. According to [4], the minimal radiant flux for white light rod vision is about $4\cdot10^{-9}lumen/m^2$. Assuming $V(\lambda)$ for white light to be 0.8, we obtain $\Phi_{min} \approx 5\cdot10^{-13}W$ under the same assumptions for D and Ω as before.

Just-perceptible luminance: Suppose the just-perceptible luminance for light of wavelength λ is $L_{min}(\lambda)$. Let S denote the area of the display and Ω the viewing angle. The total display radiant power,

$\Phi_{min}(\lambda)$, is then

$$\Phi_{min}(\lambda) = \frac{L_{min}(\lambda) \cdot S \cdot \Omega}{683 \cdot V(\lambda)}$$

For white light, L_{min} has been determined to be $7.5 \cdot 10^{-7} candella/m^2$ [4]. With the same assumptions as above, the minimal radiant power for a $12.1''$ laptop display and white light is about $5 \cdot 10^{-11} W$. For comfortable reading, the luminance level is, however, about $\frac{100}{\pi}\ candella/m^2$ [4], which requires a radiant power of about $2mW$ for a $12.1''$ display. This minimal radiant power for comfortable reading is about seven orders of magnitude larger than the just-perceptible threshold.

2) Auditory output: Let Ω denote the solid hearing angle and D the distance between ears and the sound source. The minimal sound intensity human beings can hear is about $10^{-12} W/m^2$ for a sound field of relatively long duration ($>300ms$) [12]. Below $300ms$, the threshold sound intensity increases fast as the sound duration decreases [12]. Therefore, we can estimate the minimal energy, E_{min}, for human beings to detect one bit of auditory information to be

$$E_{min} = 10^{-12} \cdot 300 \cdot 10^{-3} \Omega D^2$$

Assuming $\Omega = 0.125\pi\ sr$ and $D = 0.3m$, we have $E_{min} \approx 10^{-14} J$, which is of the same order of magnitude as the minimal energy required for displaying one bit of visual information. Note that the minimal sound intensity varies for sounds of different frequencies. $10^{-12} W/m^2$ is approximately the just-perceptible intensity of sound at a $1000Hz$ frequency, which belongs to the span of frequencies human beings are most sensitive to. A normal conversation generates a sound level that is about 10^6 times larger than the just-perceptible sound intensity. Therefore, for a user to obtain auditory information from a computing system, the sound intensity should be no less than $10^{-6} W/m^2$. For the values of Ω and D given above, this results in an acoustic energy requirement of about $10^{-8} J$. Moreover, the above thresholds assume no noise (just-perceptible intensity) or relatively low noise (conversational intensity). When ambient noise increases, the output sound level has to increase accordingly, according to Webber's Law [12].

3) Power reduction techniques: Based on the above discussion, we can formulate the power requirement of a visual/auditory output as follows

$$P \propto \frac{\Omega \cdot D^2}{\eta(\lambda) \cdot V(\lambda)} \quad (1)$$

where $\eta(\lambda)$ is the conversion efficiency from electrical power to light/sound radiant power for wavelength λ, and $V(\lambda)$ the relative human sensitivity factor. Most display research efforts have been devoted to improving $\eta(\lambda)$ by adopting new display devices. For organic light-emitting devices (OLEDs), the best $\eta(\lambda)$ so far is $70 lumen/W$ for $\lambda = 550nm$ [10]. This is about 10-fold smaller than the theoretical $683 lumen/W$ upper limit [4].

Reducing the viewing/hearing distance D seems to be the most effective way to reduce output power requirement. Unfortunately, it poses a practical problem for visual output since it requires changes to the way a display is used. Moreover, reducing D may also have an impact on other display parameters such as pixel size and aperture (the ratio of the effective area to display area). A head-mounted display is a successful example where a reduced D is used. However, it is promising only for limited scenarios such as military and virtual reality applications at this moment. Unlike head-mounted displays, their auditory counterparts, earphones, are quite popular. Due to their extremely small D and Ω, earphones are much more power-efficient than loudspeakers, as we will see in Section III.

Moreover, many applications do not need a large viewing/hearing angle. The viewing/hearing angle can be controlled to reduce output power consumption too. Another hint from Equation (1) is that choosing the colors/sounds with a higher human sensitivity, thus higher $V(\lambda)$, will also reduce power. Human vision sensitivities to different colors differ by several orders of magnitude. However, user experience with colors is quite complicated since color contrast and aesthetics also matter.

B. Input/Output Speed

The energy consumption per task depends not only on system power consumption but also on the task duration, or speed. We next characterize input/output speeds for human-computer interaction, which will be used to compare the energy efficiency of different interfacing technologies in Section IV. This subsection draws upon many previous surveys [1].

Speaking/Listening/Reading speeds: 150 words per minute (wpm) is regarded as normal for conversational English for both speaking and listening. When speaking to computers, users tend to be slower at about $100wpm$ [20]. Also, users can listen to compressed speech at about $210wpm$ [29]. Such speaking and listening rates set limits to the energy efficiency of speech-based interfaces, as shown in Section IV. Moreover, when speech-recognition errors have to be corrected, the speaking rate is reduced drastically to as low as $25wpm$ [20]. For reading printed English text, 250 to $300wpm$ is considered typical [5]

Text entry: Text entry on handheld devices is well-known to be much slower than on PCs with a full-size QWERTY keyboard. Table I summarizes results from the literature about input speeds for popular text entry methods available on commercial handheld computers, such as HP iPAQ and Sharp Zaurus, which are studied in this work. "Typical speed" refers to the raw speed regardless of accuracy while "Corrected speed" refers to real speed when error correction is taken into consideration. Note that handwriting speed is for hand-printing, which serves as an upper bound for the input speed for any handwriting recognition-based text entry. The corrected word per minute ($cwpm$) for handwriting recognition is around 7 [8]. We assume that the error rate is low for hardware mini-keyboard thumbing, $i.e.$, typing with two thumbs, and error correction is fast, as assumed for the virtual keyboard in [8].

TABLE I
TYPICAL TEXT-ENTRY SPEEDS FOR DIFFERENT METHODS

Method	Typical speed (wpm)	Corrected speed ($cwpm$)
Hardware mini-keyboard	23 [33]	22
Virtual keyboard	13 [32]	12 [8]
Handwriting	15 [25]	N/A

Stylus/touch-screen: For GUI-based human-computer interaction, the speed is usually dependent on how fast the user can respond to the GUI. In [37], we characterized the user delays and investigated how they could be predicted for aggressive power management. As we are more interested in typical delays for energy-efficiency evaluation, we assume that a 500 to $1000ms$ user delay is typical for GUI operations on handheld devices.

III. Energy Characterization

The previous section demonstrated that human factors impose limits on both interfacing power consumption and interaction speed. It also offered the theoretical minimum power requirements for interfacing. Although such minimum power requirements are orders of magnitude larger than those for computing, they are still far from the reach of the state of the art user interfaces as we will see in this section.

A. Characterization Setup

Table II provides information on system settings and input methods for the two handheld computers characterized in this work. iPAQ is also equipped with Bluetooth. Note that several different handwriting recognition schemes are available on both computers. The user can input text letter-by-letter using *letter* or *block recognition* on both computers. The user can also input a group of letters using Microsoft *Transcriber* [27] on the iPAQ.

TABLE II
SYSTEM INFORMATION FOR IPAQ AND ZAURUS

	iPAQ	Zaurus
Model	HP iPAQ 4350	Sharp SL5600
SoC	Intel XScale $400MHz$	
Storage	$32MB$ ROM, $64MB$ RAM	$16MB$ ROM, $64MB$ RAM
Display	240×320, 16-bit color	
	Transflective/back light	Reflective/front light
OS	MS Pocket PC 2003	Embedix Plus PDA 2.0 (Linux 2.4.18)
Battery	$1560mAh/3.7V$	$1700mAh/3.7V$
Text entry	Touch-screen with stylus	
	Hardware mini-keyboard (QWERTY)	
	Virtual keyboard (QWERTY)	
	Handwriting recognition	
Image/Video	N/A	CF digital camera
Audio	Integrated mic., speaker & headphone jack	
Speech recog.	Voice Command [28]	N/A

Power measurements: Power measurements are obtained by measuring the voltage drop across a $100m\Omega$ sense resistor in series with the $5V$ power supply cord. The measurement system consists of a Windows XP PC with a GPIB card and an HP Agilent 34401A digital multimeter. A program, developed with Visual C++, runs on the PC and controls the digital multimeter to measure the voltage value. The value is sampled about 200 times per second.

Basic power breakdown: We first characterize the power consumption due to hardware activities initiated by user interaction. We use the power consumption of idle PDAs (in the IDLE mode) with the display off as the baseline, and present the power consumption of additional hardware activities as extra power consumption relative to the baseline. The extra power/energy consumption [36] of an event is obtained through two measurements: one for the system power/energy consumption during the period an event of interest occurs; the other for the system power/energy consumption during the same period when the event does not occur. For example, the extra power consumption of the LCD is obtained by subtracting the system power when the system is idle and the LCD is off from that when the system is idle and the LCD is on. The power characterization results are presented in Fig. 1. In this figure, "BT Trans." refers to Bluetooth transmitting data at 9.6 Kbps; "BT Paging" refers to Bluetooth seeking a connection with another device, and "Comp." refers to measurements when the system is executing a discrete-cosine transform (DCT) application repeatedly.

B. Visual Interfaces

We first examine visual interfaces.

Graphical user interface: In [36], we presented a comprehensive analysis of the system energy consumption required for GUI manipulations. In [37], we

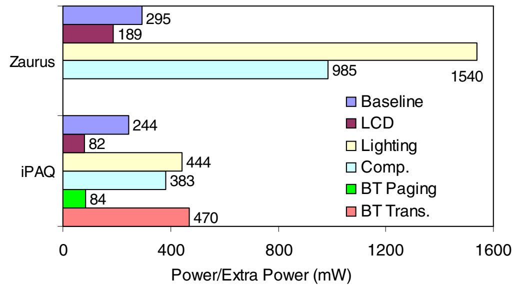


Fig. 1. Baseline power and extra hardware power consumption

showed, however, that most of the system energy is consumed when the system waits for the next user input. If we ignore the extra energy consumed by the system to generate a GUI response, GUI manipulation-based interfaces basically consume energy through a static display and an idle system. As pointed out in [36], the most effective system energy reduction strategy is to improve user productivity so that more tasks can be accomplished given the same battery lifetime. In Section IV, the energy efficiency of GUIs is compared with other interfacing technologies based on the length of the corresponding GUI operation.

Visual input: Gesture recognition and lip-reading have been proposed as possible techniques for multi-modal human-computer interaction. Both require video or image input. We used a CF digital camera card on Zaurus to obtain its power cost. When the camera is turned on with a 480×320 resolution and faces a static object, the system consumes about $1.35W$. When the object moves, the power consumption increases slightly to about $1.36W$. This is close to the power consumption when the user is preparing for a shot, $e.g.$, adjusting the focus and view. Also, it takes about $0.33J$ to capture a 480×320 picture. Since a user usually takes more than a few seconds to prepare a shot, it is obvious that it is more important to reduce the user's preparation time and system power consumption during that time than reduce these for actually capturing the picture.

C. Auditory Interfaces

We next examine the auditory interfaces available on iPAQ and Zaurus.

1) Direct recording and playback: An auditory signal can be directly recorded and played back for interfacing purposes. Direct recording is often used for note-taking and direct playback for short sound responses from the computers such as warnings and notifications. If there are too many sound responses to be feasible for direct playback, speech synthesis is required.

Direct recording: iPAQ provides a hardware button to start recording ($11KHz$ 16-bit Mono), which is very useful for audio note-taking. The recording consumes $525mW$. The extra power consumption is thus $199mW$. Zaurus draws about $198mW$ extra power consumption when recording ($16KHz$ 16-bit Mono).

Direct playback: A WAV sound clip ($32KHz$ 16-bit mono) was played on both iPAQ and Zaurus. To separate the power consumption of the speaker subsystem, the clip was played at different volumes. Table III shows the power consumption under various scenarios. "Half" volume assumes that the volume controller is set at the half mark on each system. In this scenario, the clip is not comfortably enjoyable on either system, even in a quiet office environment, if the system is about two feet from the user head. All the system power numbers include that consumed by the LCD.

The extra power consumption of the speaker subsystem is obtained by comparing the system power consumption before and after the system is muted. This has a significant impact on system power efficiency if the auditory output is used. Notably, using an earphone instead of the built-in loudspeaker reduces power by more than $300mW$ and $410mW$ for iPAQ and Zaurus, respectively. The data also indicate that using a simpler audio format (WAV as opposed to MP3) reduces power consumption at the cost of increasing the storage requirement. Since the extra power consumption of the speaker subsystem for playing MP3 is similar to that for playing WAV, the power consumption for playing MP3 at different volumes is not presented.

2) Speech recognition and synthesis: We next examine the Microsoft Voice Command [28] on iPAQ to obtain its power for a speech recognition-based interface. Voice Command is similar to the MiPad Tap & Talk system [22] except that synthesized speech is used as feedback to the user. Not having a detailed knowledge of its implementation, we adopted a black-box approach. We recorded both the power trace and the audio input/output and then aligned them to divide the power trace into meaningful segments. We fed different inputs to Voice Command to elicit certain behaviors from it.

Speech acquisition without speech being detected: We first evaluated Voice Command under no sound. Hence, the speech detection module does not detect any speech. A reasonable speech recognition implementation will discard most of the acquired speech without performing feature extraction under this scenario. Therefore, the power consumption can be attributed to the microphone subsystem and speech detection module. From the power trace, we observed that Voice Command calls the speech detection module about every $250ms$. Each call contributes to a peak in the power trace, leading to an average extra power consumption of $126mW$.

Speech acquisition with speech being detected: We next evaluated Voice Command when fed with irrel-

TABLE III
POWER CONSUMPTION FOR DIFFERENT AUDITORY OUTPUTS

Format	Volume	iPAQ (mW)			Zaurus (mW)		
		System	Extra	Speaker	System	Extra	Speaker
WAV	Max.	747	420	367	1,030	546	422
	Half	552	232	172	637	153	29
	Muted	380	53	0	608	124	0
	Earphone Max.	445	118	65	619	135	11
MP3	Earphone Max.	476	149	N/A	632	148	N/A

evant utterances, which are detected as speech but not recognized. The power trace generated was very similar to the one when there was no speech except that the peaks became wider when the input utterances became more continuous. These wider peaks can be attributed to feature extraction performed immediately after speech is detected and recognition decoding after a certain amount of speech is detected. The typical power consumption for processing a continuous irrelevant utterance is about $780mW$. Interestingly, if the utterance is relevant or recognizable, the average power consumption is actually much lower. For all the traces we obtained with a valid command, the power consumption is usually about $680mW$ in this case. The higher power consumption with irrelevant utterances may be introduced by a larger search space. For valid utterances, the search space can be significantly pruned because some very promising search paths can be identified early.

Speech synthesis: We recorded the power trace for iPAQ when it synthesized the speech output for speech recognition. The extra power consumption for the speaker subsystem at maximum volume is $181mW$, which is significantly smaller than that shown in Table III. This is due to the fact that the sound clip used for generating the table is a continuous flow of music while the synthesized speech output only uses the speaker subsystem intermittently, leading to a much lower duty-cycle. The non-speaker subsystem power for speech synthesis is about $75mW$. Compared to the $383mW$ extra power required for performing DCT (see Fig. 1), such a speech synthesis is not computationally demanding on iPAQ at all.

It is worth noting that for many voice commands, the display need not be on. This means that 82 to $526mW$ ($82 + 444$) power reduction is possible (see Fig. 1). As we will see in Section IV, speech recognition-based interfaces are more energy-efficient in many scenarios only if the display is turned off compared to several other interfacing technologies.

D. Manual Input Techniques

We next characterize the extra energy consumption for various manual input techniques for text entry. For letter-based input, such as letter recognition and virtual keyboard, we examine the extra energy consumption for inputting a letter; for word-based input, such as *Transcriber*, we examine the extra energy consumption for inputting words of different lengths. Table IV presents the extra energy consumption for inputting a letter. Fig. 2 presents the extra energy consumption for inputting words of different lengths using *Transcriber* on iPAQ. The energy consumption per letter increases slightly as the word becomes longer due to a larger recognition effort.

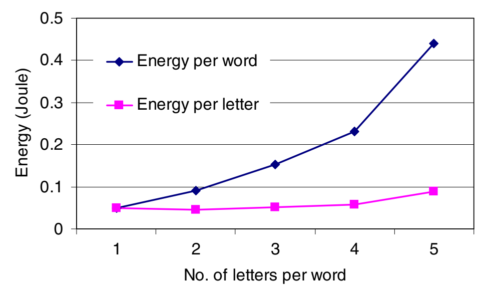


Fig. 2. Extra energy per word/letter for *Transcriber*

The above text-entry methods consume energy through touch-screen usage and related CPU activities. However, the energy thus consumed is insignificant compared to that consumed by the LCD, which needs to be on during text entry. Therefore, the energy cost per letter is not the only indicator of the energy efficiency of a text entry method. What matters more is the entry speed, as we will see in Section IV.

TABLE IV
EXTRA ENERGY CONSUMPTION FOR INPUTTING A LETTER

Input method	Extra energy (mJ)	
	iPAQ	Zaurus
Hardware keyboard	∼30	∼50
Virtual keyboard	∼10	∼80
Letter recognition	∼30	∼330

IV. A Comparative Study

Based on the discussion of interaction speeds and energy characterization presented in Sections II and III, we next compare the energy efficiency of different user interfaces. As speech-based interfaces are gaining ground, we use such an interface as the baseline.

A. Output

We first examine the energy efficiency for presenting language-based information through speech or text.

When the information to be presented is long enough, the reading/speaking rate determines the duration of presentation. Let R_{spk} denote a comfortable speaking rate and R_{rd} a comfortable reading rate in wpm. Let P_{txt} denote the system power consumption for presenting text. For simplicity, we assume that P_{txt} is roughly constant for presenting any text. We ignore the energy consumed to render the GUI for the text. The computer is basically idle after the text is presented on the display. On the contrary, the computer has to be active when the text is spoken back to the user. Let P_{spk} denote the corresponding system power consumption.

The ratio of energy consumption for text and speech outputs is therefore

$$r_{output} = \frac{R_{spk}}{R_{rd}} \cdot \frac{P_{txt}}{P_{spk}}$$

The following techniques can impact r_{output}: P_{spk} can be changed drastically by turning the display on or off or by using an earphone instead of the loudspeaker; P_{txt} can be reduced by employing aggressive power management [2], [37]. Fig. 3 gives different values of r_{output} for iPAQ and Zaurus under some possible scenarios based on data presented in Section III. We assume $R_{rd} = 250wpm$ and $R_{spk} = 150wpm$. "Light" indicates that the back light or front light is on and "PM" or "NPM" refers to whether aggressive power management [2], [37] is employed or not. The X-axis denotes whether the display, together with lighting for "Light," is on or off and whether the built-in loudspeaker or earphone is used for speech output. For Zaurus, the direct playback power consumption is used as P_{spk}. Note that the speech output is more energy-efficient if and only if the ratio is greater than 1.

For iPAQ, when the back light is on for night-time text reading, a synthesized speech output through an earphone with the display off would be more energy-efficient than a text output. For Zaurus, a speech output consistently consumes more energy for day-time usage when the front light is not needed. It is more energy-efficient only when the display does not need to be on. Its advantage primarily comes from the fact that the speech output does not mandate that the power-hungry display be on. On the other hand, it consumes two to three times more energy if the loudspeaker is used and the display is left on. *The key to improving energy efficiency for a speech output is therefore to turn off the display and adopt a low-power audio delivery method other than a loudspeaker.*

When the information is very short, such as short messages and notifications, the presentation duration is not primarily determined by the reading/speaking rate but other time overheads for eye/hand movements and distraction. Therefore, speech and audio delivery can be very energy-efficient [11], [31] since it is not visually intrusive and persistent. Such short messages and notifications, if delivered as GUI presentations, could interrupt user's ongoing work and require user action to respond, $e.g.$, to close the popup message box, leading to a larger energy overhead.

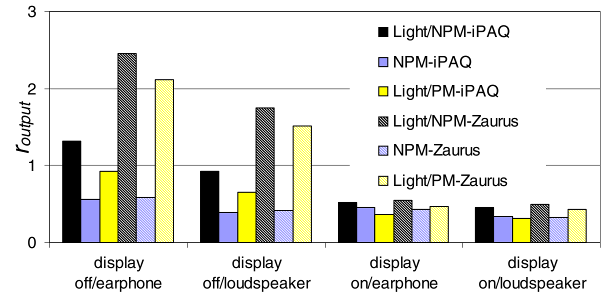


Fig. 3. Ratio of system energy consumptions for text output over speech output under different scenarios

B. Input

Next, we compare the energy efficiency of different input methods. There are two types of input, namely, text and control.

Text entry: In Section III-D, we derived the extra energy consumption for inputting a letter under different text-entry methods. As pointed out in Section II-B, the corresponding input speeds vary a lot. Let R_{entry} denote the typical input speed in wpm. Let e denote the extra energy consumed for inputting one letter using the method characterized in Section III-D and P_{idle} denote the system idle-time power consumption. We assume an average word requires six letter inputs [5], including a space. On the other hand, let R_{spk} denote a comfortable speaking rate for recognition-based input and P_{recog} the system power consumption during speech recognition. If we ignore the energy consumed during the delay between the end of speech and the end of speech recognition, the ratio of the energy consumptions for manual text entries and speech-based text entries is given by

$$r_{input} = \frac{\frac{P_{idle}}{R_{entry}} \cdot 60 + e \cdot 6}{\frac{P_{recog}}{R_{spk}} \cdot 60} = \frac{R_{spk} \cdot P_{idle}}{R_{entry} \cdot P_{recog}} + \frac{e \cdot R_{spk}}{10 \cdot P_{recog}}$$

Obviously, the energy efficiency of an input method is primarily determined by its input speed.

Although Voice Command is not intended for text entry, we assume speech recognition-based text entry would have similar power characteristics and therefore use the power consumed by the Voice Command recognition process (P_{recog}). Fig. 4 plots the r_{input} for the hardware mini-keyboard (HW MKB), virtual keyboard (VKB), and letter recognition (Letter Recog.) using data from Sections II and III. For each method, four cases are shown. "ideal" refers to typical input speed

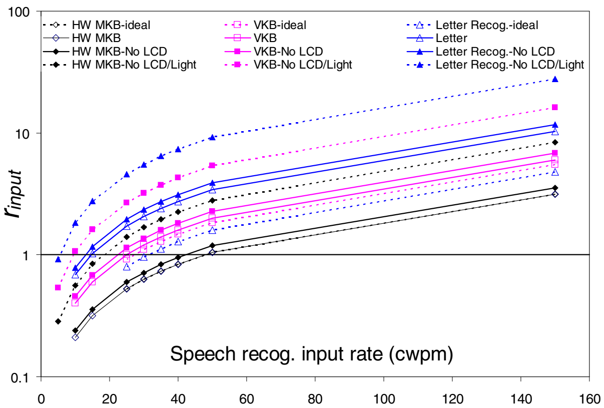


Fig. 4. Ratio of system energy consumption for different text-entry methods over speech-based text entry

without considering error correction; "No LCD" refers to comparisons to speech recognition with the display off; "No LCD/Light" refers to night-time usage with the back light on as compared to speech recognition with the display off. Except for "ideal," input speeds are expressed in $cwpm$. The break-even line with r_{input} equal to 1 is also shown. For any point above this line, the speech recognition-based input is more energy-efficient. From Fig. 4, the potential energy advantages for speech recognition-based text input are obvious since speech is potentially much faster than any other text input method. However, a recognition-based input method usually incurs much higher input errors, leading to a much lower speed in $cwpm$. For example, the speed of handwriting recognition is about half the speed of handwriting. Studies in [8] have shown that speech recognition speeds of $17cwpm$ are already available and may reach 45 to $50cwpm$ in the near future. If the power consumption for correcting errors in speech recognition is about the same as the power consumption during recognition, Fig. 4 shows that speech recognition is already more energy-efficient than letter recognition and also the virtual keyboard for night-time usage if the speech recognition-based interface does not require the display to be on. Moreover, when a speed of 45 to $50cwpm$ is achieved by the speech recognition-based interface, it will be more energy-efficient than most text-entry methods, even the hardware mini-keyboard.

Command and control: Error correction drastically decreases the input speed for speech recognition-based text entry, leading to a much lower energy efficiency. For command/control applications such as Voice Command, however, errors can be corrected much faster, *e.g.*, by reissuing the command. Moreover, for such applications, the recognition accuracy is usually much higher. This leads to a higher throughput and thus a higher energy efficiency. For a command/control task, let us assume it may take M stylus taps or it may

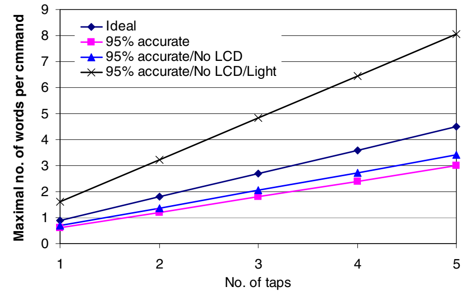


Fig. 5. The maximal number of words per command for better energy efficiency

take a W-word voice command. Let N denote the speaking rate in $cwpm$. Based on the traces collected for PDA usage [37], we assume each stylus tap is accompanied by a $750ms$ user delay, which is mostly an underestimation for typical menu selections on iPAQ. Moreover, we assume that the energy consumed by the GUI response can be ignored compared to that consumed during the user delay. Therefore, r_{cc}, which represents the ratio of the energy consumptions by GUI-based and speech-based command/control, is given by:

$$r_{cc} = \frac{P_{idle}}{P_{recog}} \cdot \frac{M{\cdot}N{\cdot}0.75}{60{\cdot}W}$$

Obviously, the shorter a voice command, the more energy-efficient it is. Fig. 5 shows the maximal number of words per command required so that speech-based command/control is more energy-efficient than GUI operations with different numbers of taps under various scenarios. 100% accurate speech recognition with $N = 150$ is used to draw the "ideal" line. Note that $150wpm$ is regarded as the conversational English speaking rate. In other cases, 95% speech recognition accuracy is used with $N = 100$, assuming 10 times more energy/time required to correct an error compared to speech recognition. Such an assumption is pessimistic since most errors can be corrected by simply reissuing the command. "No LCD" and "No LCD/Light" have the same meaning as in Fig. 4.

Fig. 5 shows that *a one-word voice command is more energy-efficient than GUI operations with two or more taps*. If the display can be turned off for speech-based command/control, its advantage is higher.

Taking notes: Speech and handwriting recognition-based text entries are mostly hindered by their low accuracy and high cost for correcting errors. However, if text transcription is not needed in real-time, *e.g.*, when using audio recording or handwriting to take a note, it is most energy-efficient to use speech since speaking is much faster than any other input method. However, if the note has to be retrieved in the format that it was recorded before recharging, there is a tradeoff between the energy consumptions for taking a note and for retrieving it, especially when it has to be retrieved multiple times.

C. Observations

The energy characterization and comparison presented so far have provided concrete and practical justifications for defining system energy efficiency as $\frac{\text{User productivity}}{\text{Average power consumption}}$. Based on such a characterization and comparison, we can make the following observations for improving energy efficiency.

Speed matters: The faster a task is accomplished and the higher the user productivity, the more energy-efficient the system usually is. From this perspective, *interface designers share a significant responsibility for designing an energy-efficient system*. In most cases, improving user productivity may incur average power consumption increase. As long as the productivity improvement percentage is larger than average power increase percentage, the system energy efficiency is improved.

In terms of the specific interfacing methods, speech-based input stands out since speech is inherently much faster than other input methods. For recognition-based input, such as handwriting and speech recognition, accuracy is important due to the high cost of correcting errors. Thus, accuracy is also important for system energy efficiency.

Display matters: The energy efficiency for a display-based interface suffers a lot since its average power consumption includes that of the display, which is large. Touchscreen/stylus-based interaction basically integrates the input hardware with the output hardware, leading to a high power consumption even for making an input, especially for night-time usage. When the power-hungry display has to be on with a slow input rate, $e.g.$, for all the manual text-entry methods, energy efficiency is drastically reduced. Speech-based interfaces again may enjoy an energy efficiency advantage since their display usage can be carefully avoided.

The power consumption landscape, however, is likely to change in a few years due to progress in new display technologies. OLEDs [10] promise high-quality low-power flexible displays for mobile computers. More importantly, bistable display technologies [21], [35] will reduce the static power consumption to nearly zero. This will significantly reduce the energy that a system spends in waiting for user inputs.

Audio matters: Surprisingly, our energy characterization results showed that the speaker subsystem is also power-hungry, drawing as much as $367mW$ and $422mW$ of power for iPAQ and Zaurus, respectively. This power consumption can be drastically reduced by using earphones instead of loudspeakers. However, the wires connecting the earphones may impact other usage issues. Since Bluetooth consumes more than $470mW$ extra power when actively transmitting data (see “BT Trans.” in Fig. 1), a Bluetooth headset is unlikely to reduce the audio delivery power consumption. Therefore, *for better exploiting the speed of speech-based interfaces, low-power wireless voice stream delivery between the user and computer is critical*.

Fig. 6. The prototype of a watch as the interface cache for iPAQ

V. Interface Cache

In the previous sections, we investigated how human factors limit energy efficiency for handheld computer interfaces, characterized different interfacing methods, and presented a comparative study for them. Since the computer responds to the user much faster than the latter responds to the former, an increasingly powerful computer, in terms of display and processor, has to spend most of its time and energy waiting for a consistently slow user. Such a speed mismatch is essentially imposed by human capacity and is growing, leading to a bottleneck in energy efficiency even for a system with a perfect user interface. The cache solution to address the speed gap between the processor and memory in conventional architectures [15] motivated us to design a low-power wireless device, to which the host computer can outsource simple interactive tasks. As an interfacing solution to alleviate the energy efficiency bottleneck due to a slow user, such a device functions like a cache for more expensive interfaces on the host, reducing interfacing energy requirements without sacrificing user productivity much. Its design and prototype are discussed next.

A. Wireless Cache for Interfacing

The cache device we designed and prototyped takes the form of a wrist-watch that communicates with a handheld computer wirelessly. The watch prototype and its host, the iPAQ used in the characterization, are shown in Fig. 6.

As an interface cache, the watch provides the host computer with a limited display. It provides two different services: active and passive. The watch stays connected with the host and waits for user input for the active service. The user input can be echoed on the watch in real-time. For passive service, the watch communicates with the host from time to time to receive data. The connection can be closed after data transmission but the user can still access the data cached on the watch. The watch provides its services through a simple application-layer protocol, called the synchronization protocol. It is up to the host computer to determine what and how to display and how the connection is managed using the protocol. The watch simply follows instructions from the host computer as a slave.

Hardware components: The watch consists of three major components: a Microchip PIC16LF88 microcontroller, a 2×8 monochrome character LCD, and a Bluetooth-RS232 adapter (Promi-ESD class II) from Initium [17]. One MAX604 linear regulator is also used. The system is powered by a 3.6V supply with three $800mAh$ rechargeable AAA batteries. The microcontroller is run at a $10MHz$ clock frequency, drawing a current of less than $0.6mA$. It drives the LCD module directly but controls the Bluetooth adapter through a $9.6Kbps$ serial port. The LCD module draws a current of about $1mA$. There is no lighting for the LCD module in the prototype, a limitation of the current implementation that can be easily alleviated. Therefore, we assume that the LCD module can be used at night time in the following discussion.

The Bluetooth-RS232 adapter implements the simplest Bluetooth application profile, the Serial Port Profile (SPP). Two devices with Bluetooth SPP can communicate in the same way they would with an RS232 serial port connection. The Bluetooth adapter has a number of operational modes. When it is not connected or seeking connection, it is in the STANDBY mode, drawing about $6mA$ current, but can be turned off for more energy savings. In the following discussion, we use the STANDBY mode to refer to both situations. When the Bluetooth adapter is seeking connection through a Page-Scan session, it is in the PENDING mode, drawing about $19mA$ current. In the PENDING mode, it does Page-Scan for T_{ps} ms every T_{pc} ms. T_{ps} must be a multiple of a $625\mu s$ slot. Both T_{ps} and T_{pc} can be configured through commands from the RS232 serial port, leading to different average power consumption. When the Bluetooth adapter is connected, it is in the ACTIVE mode, drawing about $9mA$ current for no data transmission and about $28mA$ during active data transmission at $9.6Kbps$.

Communication design: Since the data for the passive service are not time-critical, the host buffers data for a certain period of time and a connection to the host is required only from time to time. The communication between the watch and its host computer is not data-intensive and communication occurs only sporadically. Therefore, energy consumption due to data communication is very small compared to that required to establish a connection. However, based on our energy characterization data presented in Section V-B, it is more energy-efficient to disconnect and then reestablish a connection in a cooperative fashion when the connection is required more than 30 seconds later. By "cooperative," we mean that both the watch and the host enter the PENDING mode at the same time.

When the host is connected to the watch, it schedules the next communication with the watch according to prior-history-based prediction. It then determines whether the current connection should be maintained or closed based on when the connection will be required the next time. If the connection needs to be closed, the host notifies the watch when it will seek connection next time. After receiving such a notification, the watch shuts down its Bluetooth adapter and forces it back into the PENDING mode when the specified time has elapsed. This ensures that a connection is established in a cooperative fashion, and keeps the watch and the host synchronized with a relatively low energy overhead, as we will see in Section V-B. If the watch loses synchronization with the host, they enter the PENDING mode to re-synchronize.

Software design: The software on PIC is developed using PicBasic Pro. In the main loop, PIC reads its hardware UART and interprets the data according to the synchronization protocol. Following instructions from the host or user, PIC can send AT commands to change modes for the Bluetooth adapter.

Software on the iPAQ, called *watch manager*, was developed using Embedded Visual C++ and built upon the BTAccess library [3]. The watch manager functions like a device driver. On the one hand, it implements the synchronization protocol. On the other hand, it collects information from different application software, such as Outlook, according to the user configuration. The information is buffered in the watch manager and then sent to the watch when it connects to the host. Each time it is connected to the watch, the manager schedules the next connection and notifies the watch through the synchronization protocol.

Interface design: For this prototype, we used very simple interfaces to support the targeted services: a 2×8 monochrome LCD and three tact buttons, Buttons 1, 2, 3. The user can change the watch service mode by clicking Button 3. When the watch is in the passive service mode, a Button 3 click puts the Bluetooth adapter into the PENDING mode unless the connection with the host is established. When the watch is in the active service mode, a Button 3 click simply closes the connection and brings the Bluetooth adapter back to

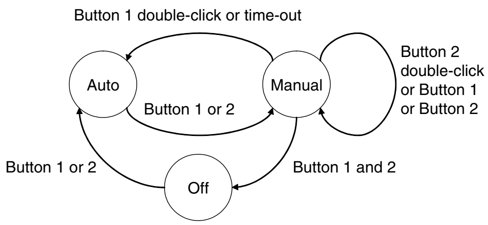


Fig. 7. State-machine description of the watch interface

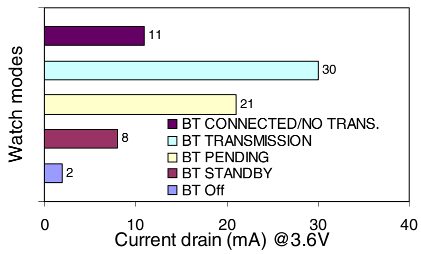


Fig. 8. Power consumption for the watch in different modes

the STANDBY mode to wait for the next scheduled connection.

In the active service mode, a Button 1 click clears the display and sends a negative confirmation back to the host, while a Button 2 click simply sends a positive confirmation. In the passive service mode, the user can use Buttons 1 and 2 to browse the text messages cached in the watch. The interface is better represented as a finite-state machine, as shown in Fig. 7. In the $Auto$ state, the watch displays valid message entries in its message cache by rolling the text messages through the first line of the LCD. Each message is rolled according to its meta-data, which specify its priority in terms of how many times it has to be repeated with each display cycle. In the $Manual$ state, the user can use Buttons 1 and 2 to browse valid entries. Clicking Button 1 induces a skip to the next valid entry whereas clicking Button 2 rolls the current message on the LCD by one letter. Double-clicking Button 2 marks the entry currently on the LCD as invalid and confirmed, which is conveyed to the host next time the watch gets connected to the host.

B. Evaluation

We evaluated the prototype watch device as the wireless cache for iPAQ in order to see whether or by how much it would improve the battery lifetime of iPAQ. Instead of using user studies and subjective metrics, we focused on evaluating the design with related objective metrics. We first present the energy characterization results and then an analysis of energy-efficiency improvement.

Since the non-Bluetooth components on the watch are not power-managed, they draw about $2mA$ current all the time. Fig. 8 presents the power consumption for the watch in terms of current consumption at 3.6V when the Bluetooth adapter is in different modes. Fig. 9 shows how the watch battery lifetime changes when the average communication interval changes. Most of the

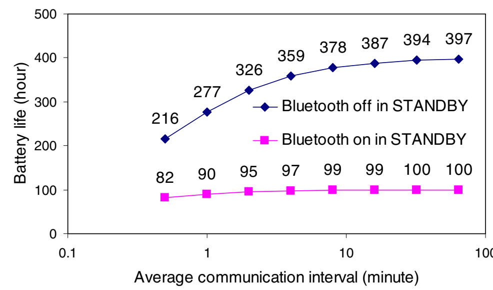
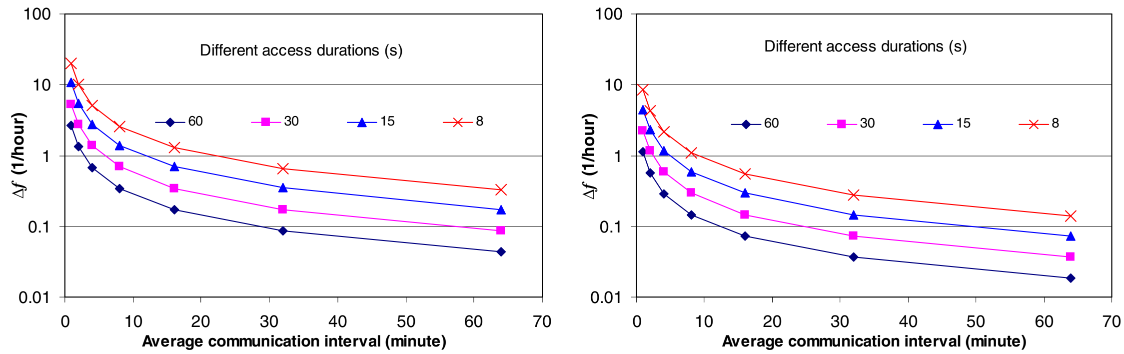


Fig. 9. Watch battery lifetime for different average communication intervals

time, the watch stays disconnected from iPAQ and there is no energy cost for Bluetooth. Assuming a typical $1KB$ data exchange each time a connection is made, the time for data exchange is about 0.118 second. The corresponding energy cost for iPAQ is $84.2mJ$ (based on a power consumption of $470 + 244 = 714mW$ from Fig. 1). Let T_p denote the time it takes the watch and iPAQ to establish a connection cooperatively and T_s denote the average interval between two communication events. Note that when iPAQ is in the PENDING mode doing Paging, the power consumption is $P_{host} = (84 + 244) = 328mW$ (see Fig. 1). On the other hand, we assume that if the watch is not used, the user has to access iPAQ directly at a frequency f with average duration of T_{access} ($f < 1/T_{access}$). The average power consumption, P_h, of iPAQ during usage, is about $(244+82+444) = 770mW$ and $(244+82) = 326mW$ with and without the back light, respectively. Let Δf denote the reduction in the iPAQ access frequency f due to the use of the watch. Therefore, using the watch improves the energy efficiency of iPAQ if

$$\frac{84.2 + P_{host} \cdot T_p}{T_s + 0.118 + T_{access}} < P_h \cdot \Delta f \cdot T_{access} \qquad (2)$$

where the left hand side gives the extra power consumption in iPAQ due to Bluetooth activities and the right hand side gives the power reduction due to reduced iPAQ accesses. Fig. 10 plots the minimal frequency reduction in terms of number of accesses per hour for the cache device to improve the iPAQ energy efficiency with different average communication intervals (T_s) and average access durations (T_{access}). Based on our measurements, $T_p = 2.5s$ is used. It presents the results for day-time (without the back light) and night-time (with the back light) access. Different lines represent different average access durations from 8 to 60 seconds. The figure clearly shows how many accesses per hour have to be outsourced to the cache device to improve the host computer energy efficiency. For day-time usage,



(a) Day-time access without the back light

(b) Night-time access with the back light

Fig. 10. Minimal frequency reduction for improving energy efficiency

if the cache communicates with the host every 30 minutes on an average, the host energy efficiency will be improved even if only two 30-second accesses or three 15-second accesses can be outsourced in a day. For night-time usage, even half the number of such outsourcings will still improve energy efficiency.

C. Design Issues

We have shown how the watch can improve the energy efficiency for the host with objective measures. Such a watch is one example of wireless interface cache devices. In the following discussion, we highlight the important issues involved in the design of such devices.

Wireless communication: In terms of form factor, wireless communication between the host and cache devices is almost mandatory. There are several wireless personal-area network (PAN) technologies intended for different data rate and application scenarios. We used Bluetooth in the current watch prototype because its availability on iPAQ and in the market facilitates prototyping. Unfortunately, Bluetooth, especially the iPAQ Bluetooth, imposes a high energy overhead for iPAQ to establish a connection with the watch. This issue can be addressed by implementing the iPAQ Bluetooth in a separate hardware system. In fact, IEEE 802.15.4 or customized radio modules with a lower power consumption, shorter connection establishment time or connectionless communication may be employed to replace Bluetooth since the required data rate is not high. This, however, requires extra hardware to be added to iPAQ.

Tasks for outsourcing: User studies will be critical for determining which tasks should be outsourced to obtain the best tradeoff between the energy efficiency of the host computer and complexity/cost of the cache device. First, instead of determining which tasks should be outsourced, the cache device designer should instead determine which input/output services the cache device should provide. For example, the watch exports its display services through the synchronization protocol and any iPAQ application can utilize such services by specifying what to display. This gives application developers and users most flexibility. Second, even if a task itself suffers productivity degradation after being outsourced to a cache device, system energy efficiency and overall productivity may still be improved. For example, browsing a text message from the watch will be slower than reading it directly from the iPAQ display. However, if the overhead for the user to take out the iPAQ and power it on/off is considered, obtaining information from the watch may even be faster. As another example, laptop usage has been shown to decrease when a BlackBerry smartphone is used [13] because a user can better utilize downtime for productivity, *e.g.*, reading/writing emails with the smartphone while waiting in a line.

Battery partition: A simple question for our interface cache proposal would be: what if we just give the extra battery capacity of the cache device to the host. In the prototype, such an extra battery capacity will give iPAQ an extra operating time of about two hours. The rationale behind a cache device is that we can achieve a longer system operating time by giving some battery capacity to a low-power interface cache device. Therefore, when designing an interface cache device, we must consider the usage patterns of both the cache and host devices and user's expectations of their battery lifetimes to achieve the best system operating time. Again, user studies will be extremely important.

D. Related Devices

Similar wrist-worn devices have been designed including the IBM Linux Watch [16] and Microsoft SPOT watch [26]. They were intended to be a self-contained computer system. If viewed as cache devices for interfacing, they lie on the other extreme of the spectrum, embracing a feature-rich and power-hungry design. Indeed, the author of [14] blamed the high price and short battery lifetime for the lackluster market reception of the Microsoft SPOT watch. They differ drastically from our design of the interface cache device, which emphasizes a low-power minimalist approach. The TiltType wrist device demonstrated in [9] displays text messages from the computer using an XML-like protocol. With a similar minimalist approach, it was investigated primarily as an input device based on TiltType. None of these devices was proposed to improve the energy efficiency of the host computer.

Related to the philosophy of using a low-power interface cache device, Intel's personal server project envisions that the personal server, a handheld computer-like device, utilizes wall-powered displays in the environment [34]. Since it can be much more energy-efficient to transmit user interface specifications wirelessly than rendering and presenting the user interfaces, such a parasitic mechanism can be another user interface solution to overcome the energy efficiency bottleneck due to a slow user.

VI. Related Work

Low-power research so far has offered many solutions centered around the computer without much regard to the way it interacts with the user, except a statistical request model. Only recently, works have been reported for interface devices such as displays [6], [7], [18], [30], [36]. Also, human factors and user interfaces are recognized as having a significant impact on system energy efficiency. Lorch and Smith [24] pointed out the importance of using user interface events for dynamic voltage scaling. In [36], we characterized the energy consumption of different graphical user interface (GUI) features on handheld computers. We pointed out the importance of idle time and user productivity in system energy efficiency. In [37], we also proposed techniques to aggressively power-manage the system during idle periods based on user-delay predictions. In [2], the authors implemented an aggressive OS-based power management scheme for exploiting idle periods on an Itsy system. Similar techniques were also implemented on the IBM Linux watch [19].

VII. Conclusions

In this work, we presented a comprehensive treatment of energy efficiency considerations for handheld computer interfaces. We showed how human capacities impose limits on system energy efficiency and characterized the energy cost for interfaces on two commercial handheld computers. Based on energy characterization, we presented a comparative study of different interfacing technologies. Specifically, we found that speech-based input has a large potential for outperforming other input methods due to the fact that a human can speak much faster than write or type. On the other hand, a speech-based output suffers from high power consumption required for audio delivery without enjoying a significant speed advantage over text-based output. We also pointed out that the speed mismatch between users and computers and power-hungry interfacing components introduce a bottleneck in system energy efficiency. To solve this problem, we proposed a low-power low-cost device to which a host computer outsources simple, yet frequent, tasks. Such a device, serving a similar goal as the cache does for memory, is called the interface cache. We designed and prototyped a Bluetooth wrist-watch as the interface cache for an HP iPAQ handheld computer. While most other digital watches were designed as complete stand-alone computer systems, our watch is designed purely to serve the host computer. The system functionality is carefully partitioned so that only minimal functionality is placed on the watch. Our experiments and analysis show that such an interface cache will be able to improve the energy efficiency of its host computer significantly.

Acknowledgments

The first version of the Bluetooth wrist-watch was designed/prototyped by Lin Zhong with Mike Sinclair while at Microsoft Research as a summer research intern. The watch was designed to form a PAN of wireless interfacing devices to provide pervasive interfacing for a handheld device like iPAQ. The authors would like to thank all the anonymous reviewers and the paper shepherd, Dr. Mark Corner, for their suggestions that significantly improved the paper.

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