Trends and Limits in the “Talk Time” of Personal Communicators

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Invited Paper

In the past, telecommunications and computing have only been possible within a few feet from a telephone jack or an ac outlet. The user interface has required hand-eye coordination, full user attention, and a working surface to operate, for example, a telephone keypad, a keyboard, or a mouse. Now, “personal communicators” with wireless connectivity, energy efficient electronics, novel user interfaces, and advanced battery technology promise to cut these tethers, and to offer convenient and natural communication and computation anytime, anywhere.

This article provides simple estimates for the energy budget for personal communicators and its evolution as technology matures. In outline, we assume personal communicators will mimic the size and weight of successful, portable objects, such as paper notebooks. From the weight, the fraction of the weight devoted to batteries, and the specific energy of modern rechargeable batteries, we estimate the energy available. Since it is desirable for this energy to last a full working day of heavy use, one can estimate the average power the communicator will draw.

Observation of people using computers and telephones gives us a typical “usage profile” describing the time spent viewing the display, computing, and/or communicating. The functionality required in each mode leads us to an estimate of the power drawn in each mode, and its trend in time.

Miniaturized transistors and wires enable circuits to operate faster at ever lower voltages: The computing ability per Watt is increasing 75% every year. In parallel, algorithms for real-time computing tasks such as handwriting and speech recognition are becoming more efficient and accurate. Thus human-machine interfaces will become increasingly natural and attractive.

I. INTRODUCTION

The benefits of telecommunication and computing have been inaccessible to mobile people who need to communicate with other (mobile) people and services at diverse locations. A primary function of a personal communicator is to facilitate such communication.

Many challenging problems, both technical and nontechnical, must be solved to build a communicator. The user interface must allow operation with the device held in the hand and receiving only partial user attention, more like a paper notebook than a personal computer. The device must be lightweight yet robust. The device must be small enough to carry, yet have a display large enough to provide a graphical user interface and to display bit mapped images such as fax pages. Finally, the time between recharging periods must be greater than the time the user is away from a charging station. Thus the communication, computation, and user interface electronics must use energy efficiently, and the battery technology must be pushed to its limits.

The following sections provide simple estimates for the energy budget of personal communicators, how we expect these to change as technology matures, and the use to which the energy is—and will be—put.

II. DESCRIPTION OF THE PERSONAL COMMUNICATOR

Personal communicators are different from portable cellular phones because they handle not only voice calls but also images and data (“integrated service”), and they provides computing power as an adjunct to communication; they are different from notebook computers and palmtop organizers in that they are foremost mobile communication devices. Thus a radio frequency (RF) wireless link (labeled 1 in Fig. 1) is the principal form of connection to a public communication network. From the network, other people or services can be reached. The wireless link allows transmission and reception of 1) circuit switched voice calls, via, for example, the Advanced Mobile Phone System (AMPS) in North America; 2) fax images; and 3) electronic mail and other messages, including electronic messages executed inside an active network (“agents”).

Transmitting bit mapped images by fax, a wireless-channel-coded version of an analog voice-band modem signal, is surely inelegant. However, it is desirable simply because fax machines are ubiquitous. Digital radios and packet switching (e.g., via the Cellular Digital Packet Data standard) will eventually replace fax transfers.

New digital standards are being adopted: Time Division Multiple Access (TDMA) standards such as the European-led Global System for Mobile communication (GSM) and

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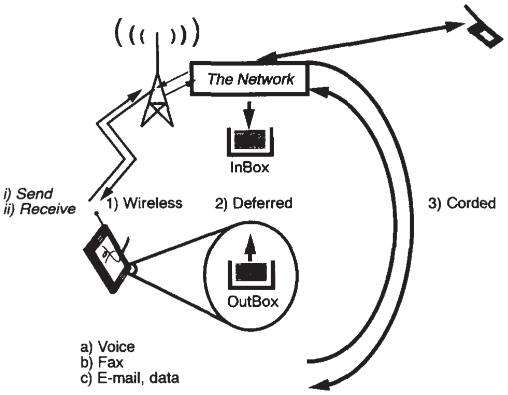

Fig. 1. The purpose of a personal communicator is to enable the user to communicate information in what ever form, irrespective of time or place.

the TIA Interim Standard 54 (IS-54); and Direct Sequence Code Division Multiple Access (DS/CDMA) such as TIA IS-95. Compared to analog service, digital service offers increased privacy, a better compromise between voice quality and capacity, and a natural path to integrated services.

RF coverage and capacity restrict the availability of the wireless link, so there must be provision for "deferred connectivity," sometimes termed batch mode transfer (labeled 2 in Fig. 1). Two storage areas per user, called the outbox and inbox, hold messages until a communications link is reestablished. Messages composed by the user when a wireless link is unavailable are stored in the outbox, on the personal communicator. Likewise, the inbox, on the network, receives voice, fax, and data messages from senders when a wireless link is inactive. The inbox is an extension of familiar voice mail systems.

Optionally, a corded link (labeled 3 in Fig. 1) such as an ordinary telephone jack may be used when available, to save the cost of wireless connectivity.

III. ESTIMATING TRENDS IN THE ENERGY BUDGET OF A PERSONAL COMMUNICATOR

A. The Weight of a Personal Communicator and Its Battery

Like many specifications of a successful communicator, the weight must be determined by nontechnological (human) factors. Fig. 2 illustrates the weight of typical successful, portable, electronic, and nonelectronic objects, such as paper notebooks and cellular phones, for consumer and business use. These are rarely over 1 lb, indeed 4–12 oz is an acceptable range. We assume the first successful personal communicators will be at the upper end of this range, i.e., ~12 oz.

What portion of this weight can be taken up by the batteries? As illustrated in Fig. 3, the weight in actual portable electronic objects is divided among the batteries and other components (casing, populated printed circuit board, and display). With the rich graphical displays required for personal communicators, the battery mass probably cannot exceed a third of the total mass (see Fig. 3. For example, a ~12 oz (~0.3 kg) device can have a 4 oz (~0.1 kg) battery, the weight of four AA-size nickel metal hydride (NiMH) batteries.

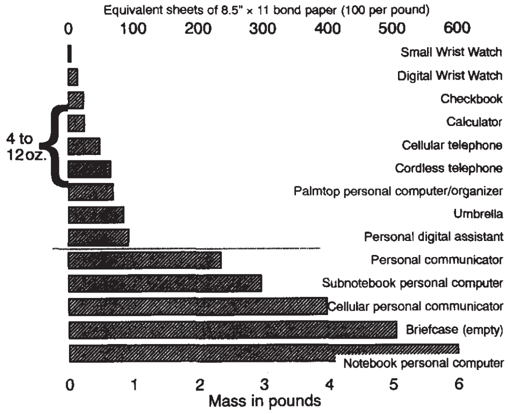

Fig. 2. Masses of a selection of familiar portable objects—electronic and nonelectronic. Objects for consumer and business use are rarely over 1 lb, objects only for business use are sometimes over a pound, up to several pounds. Paper notebooks come in all sizes, and a "paper equivalent" scale is provided above.

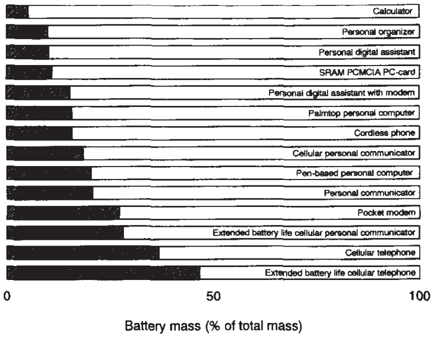

Fig. 3. Percentage of mass being battery masses of a selection of familiar portable electronic objects. With the rich graphical displays required for personal communicators, the battery mass probably cannot exceed a third of the total mass.

B. Battery Energy

Battery technology has improved continuously since the invention of the copper zinc cell in 1800 by Alessandro Volta. However, the specific energy of commercially available rechargeable batteries has improved only ~2% per year over the past 50 years. Briefly, the theoretical maximum specific energy of a given battery couple can be estimated by assuming every ionic pair in the battery provides one electron at the electrochemical potential difference of the

Table 1 Estimated Use of a Personal Communicator Over a 24–Hour Period of Heaviest Use

Mode	Typical use per day (hr)	Power Required (W)	Energy Used (W hr)	Cellular module	Processor	Random access memory	Nonvolatile memory	Display
Talk	1	2.6	2.6	Active	Active	Active	Active	Changing
Active	2	1.2	2.4	Standby	Active	Active	Active	Changing
Idle	3	0.6	1.8	Standby	Off	Retained	Retained	Static
Standby	4	0.3	1.2	Standby	Off	Retained	Retained	Off
Recharge	14	–	–	Standby	Active	Active	Active	Changing
Shutdown[a]	∼0	∼0	∼0	Off	Off	Lost	Retained	Off
TOTAL	24		8.0					

[a] The shutdown mode is only used for long term storage of the communicator

couple (e.g., ∼1.25 V for nickel cadmium (NiCd)). Batteries too close to the limit can have reliability and safety problems, and so the specific energy of typical modern NiCd cells is ∼50 W.hr/kg or only ∼15% of this limit. Higher specific energies can be achieved by using couples with a lower mass per mole, and/or a higher electrochemical potential difference. Couples containing lithium (Li) are favorable, with lithium fluoride being the best. However, Li is very reactive in metallic form, and thus difficult to use in a rechargeable battery. Production NiMH and Li ion batteries presently have specific energies of ∼55 and ∼60 Wh/kg, respectively. Li ion technology will probably improve to ∼80 Wh/kg over ∼10 years, then our ∼0.3 kg device with its ∼0.1 kg battery will have ∼8 Wh (∼30 kJ) of energy available for use between recharging periods, if we assume no breakthrough in specific energy.

C. *Energy Budgeting*

The user will draw this energy in the various modes of communicator operation between recharging opportunities, typically 10 hours away from a recharging nightstand. This gives us an estimate of the average power, namely 0.8 W. However, the actual power drawn at any one moment will vary greatly. Table 1 gives an estimate, based on our informal human factors experiments, of use of the computing and communication usage profiles, i.e. fractions of the time spent viewing the display, computing, and communicating. When using the computation facilities, the device switches frequently between "Active" and "Idle" modes as the user submits a command, the device responds actively for a few seconds, then idles while the user inspects the result on the display for several seconds. The ratio of times in active:idle modes is typically 1:2-3, so the effort the designer puts into selecting or designing a low power processor is diluted by its duty factor of 25–33%. However, the display is on 100% of the time that the user perceives the devices as "on," thus its power requirements should receive intense design attention (See Section IV-A).

When the cellular module is in standby, it must be prepared to receive incoming calls and periodically "sniff" (transmit and receive signals to and from) the cellular network. The module may be in this mode for nine hours per day, so the modal power is critical. Recent enhancements to the cellular network protocol will reduce the duty cycle of the communicators transmitter, and hence the (average) standby power.

The present day "best-in-class" power characteristics of each mode of a typical communicator are also shown in Table 1, taking an AMPS communicator as an example. Portable AMPS phones transmit up to 600 mW of RF power, but the ∼3 dB insertion loss of the transmit/receive duplexer, and the inherent efficiency of power amplifiers (∼60%)[1] mean that it draws ∼2 W from the battery.

Because of the weight is determined by human factors, and battery energy by technological limitations, we expect the *energy* used in each mode to stay relatively fixed as the 12-oz "class" of communicator improves over the years. Thus we can expect the power in each mode may either 1) decrease due to, for example, the use of microcellular base stations enabling lower transmitted power and increased talk time, or 2) stay the same, resulting in increased computing ability or increased number of pixels displayed for examples. In either case. In the next section we consider what uses increased computing ability and display quality could lead to.

IV. THE USER INTERFACE

Unlike notebook computers, personal communicators can be used in meetings, standing in warehouses, factories, or face-to-face with clients, in airport lounges, and in cars, thus novel user interfaces are required. The following subsections examine the consequences of these requirements, the present status, and technology trends.

A. *Flat Panel Displays and Digitizers*

Personal communicators have energy efficient reflective liquid crystal displays (LCD) overlaid with a stylus—or finger—driven digitizer. Unfortunately, present liquid crystal materials utilize voltage dependent birefringence and so require polarizers, which absorb most of the ambient light. This is a severe problem in weak ambient lighting conditions. The power required by a backlight (∼5 mW/cm^2) is prohibitively high for these devices.

Bond paper and xerographic ink scatter (in a cosine distribution) about 90% and 4% of the light incident upon them, respectively, a contrast ratio >20 : 1. In typical room light, a photocopy backscatters about 10–20 fL, or ∼100 μW/cm^2. Under the same conditions, present

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[1] Power amplifiers of higher efficiency can be built, but suffer from instability under varying voltage standing wave ratio (VSWR) conditions, e.g., when the antenna is brought near to a ground plane such as an automobile body.

reflective displays emit only ~10 μW/cm^2, and have a contrast ratio of only 5–10:1 (depending on the amount of multiplexing, the LCD material, the viewing angle, and whether the matrix is active or passive). Polymer dispersed liquid crystals exhibit voltage dependent light *scattering*, obviating the need for polarizers, and can appear paper-like over a wide range of viewing angle. Commercial development of such displays in expected in the next few years.

The texture of the screen surface is critical in achieving the correct friction with the stylus in order to create the feel of pen on paper, but the bloom selected must not blur out the image created by the underlying LCD. Some screen blooming technique actually enhance the contrast at selected viewing angles.

LCD's generally have fragile glass substrates. In notebook computers, a clam shell design is employed to protect the screen from scratches and fracture. For a personal communicator, a clam shell design is possible, but more robust, plastic displays would help the manufacture of light, rugged tablet-like form factors.

The electronic circuitry to store the image in digital form and to raster the LCD screen is becoming increasingly efficient. In products like Sharp's ExpertPad and OZ-9600, frame buffer chips with dense packaging technology are placed on the LCD panel. The frame buffer eliminates the need for continuous refresh from an external display controller. When the image on the display is not changing (which is most of the time), power is reduced to 5–8 mW compared to 100 mW otherwise [1]. As chips with denser I/O become cheap enough for a consumer product, this technique will become applicable to larger and larger panels.

Displaying a fax that is composed on the communicator with a known set of fonts and shapes is less demanding than displaying an arbitrary, incoming, bit-mapped fax. A regular fax machine prints the 1728 × 2376 pixels of a Group 3 fax on a 8 1/2″ × 11″ sheet of paper at 216 dots per inch, with 1-bit of depth (i.e., black or white, no gray). On a communicator, the LCD has a much lower number of pixels, ranging from a half CGA (200 × 320) up to a VGA display (480 pixels × 640 pixels). Software can allow the user can "zoom-in" on a portion of the document to examine any fine detail, but this can be tedious. Whole faxes can, however, be displayed legibly on a VGA LCD using a temporal dither algorithm. Software controls duty cycle and hence the apparent darkness of each display pixel in proportion to the number of black pixels in a square cluster of pixels on the original fax, giving 2 or 3 b of depth (i.e., 4 or 8 gray levels). Unfortunately, the bandwidth to the panel, and hence the power dissipation, rises in proportion to the number of gray levels.

Bit mapped images (like fax) require large amounts of storage compared to other documents. Without compression, each page would takes 501.2 Kbytes. In contrast, 60 lines of computer text, each 70 characters wide, uses only 4.2 Kbytes (240 pages per megabyte of user storage). Group 3 fax uses a modified Huffman coding yielding an ~8 ×compression ratio on typical pages, yielding 63 Kbytes per page but still only 13 pages per megabyte can be stored. Thus bit mapped images affect the battery life in two ways: via the display and power to load and store data from memory.

Table 2 Typical Output Rates from Device to User

Mode	Words per minute
Reading	360
Listening	250

Table 3 Typical Input Rates from User to Device

Mode	Note	Words per minute
Speaking	News announcer	180
	Typical	150
	Literature reading	120
Typing	Top Rank	135
	Skilled	55
	Nonsecretarial Typist	40
	Palmtop keyboard	20
	On-screen "keyboard"	15
	Hunt and Peck	10
Writing	Shorthand	130
	Cursive	24
	Block	18

B. Ease of Use

Graphical user interfaces on desktop computers are rich in features and require the user's full attention. In contrast, personal communicators should be simple to use, without ever having to read an instruction manual, and without having to divert attention from other tasks, such as listening to the speaker at a meeting or, importantly, driving a car. This is a very challenging area of human factors research [2]. Two example of novel graphical user interfaces are prototypes of pen-based user interfaces for communications applications [3] and the Magic Cap communication applications platform of General Magic Inc., which allows the user to tap the pen on cartoon-like images to interact with internal and on-line information [4]. Handwriting recognition is not necessary in Magic Cap.

C. Novel Input Modes

Handwriting and speech recognition enable a more natural human-machine interface. Tables 2 and 3 give typical input and output rates for these methods, assuming perfect accuracy, in comparison to traditional computer keyboards [5], miniature "palmtop" keyboards, and on-screen keyboards (where the user taps the digitizer stylus on an LCD image of a keyboard).

Voice command spotting and computer generated speech are valuable for placing a call in a car without touching the communicator and are available now in some cellular car telephones and pocket organizers.

Full vocabulary speech recognition, i.e., using the communicator as an automatically transcribing dictation machine, may one day be possible for authoring a large document, in situations where sufficient privacy is available.

Table 4 Approximate Computational Load of Some Real Time and Near Real Time Algorithms

Application	Algorithm	Notes	DSP MIPS	μP MIPS
Voice Coding	ADPCM	24-32 kb/s	0.5	2
	SubBand	16-24 kb/s	2	8
	GSM	13 kb/s	6	24
	CELP	5-8 kb/s	25	100
Fax/Modem	V.22	2.4 kb/s	2	8
	V.32/bis	9.6-14.4 kb/s	22	88
Speakerphone	Half Duplex		1	4
	Full Duplex		20	80
Voice Recognition	Isolated Word	Speaker trained	0.4/word	1.6/word
	Connected Word	Speaker independent	1/word	4/word
	Sub-word	Speaker independent	2/word	8/word

Electronic images of stylus strokes ("ink"), and handwriting recognition can be used for taking short notes unobtrusively, with the stylus doubling as a pointing device.

Algorithms for recognition often involve calculation of the dot product of a feature vector with a template vector, and digital signal processor (DSP's) are cost effective for this type of task. Typically, a DSP can multiply and accumulate two operands of its native data type (usually a 16 b integer) per instruction cycle. The computing ability required for such algorithms are given in Table 4 in terms of millions of DSP instructions per second (MIPS) and compared to some communications algorithms that are used in communicators [6]. With the increasing use of near real-time translation and real-time communications algorithms, it is expected that personal communicators will make extensive use of low-cost DSP's. This DSP resource will be managed by the system processor: one of the popular microprocessor cores integrated with control and peripheral logic.

Present algorithms are far from perfect. Fig. 4 shows the effects of imperfect translation of handwritten text. It takes about six times longer to correct a word as it does to write it. Thus a translation rate $\geq \sim 300$ words per minute and an error rate $\leq \sim 1\%$ is required to approach the natural input rate. The required error rate is less than the error rate of a careful human recognizer on isolated lower case characters [7], which is $\sim 9\%$. With the present word error rate of $\sim 7\%$, frequent corrections are necessary, giving a net input rate even below that for an on-screen keyboard. However, accuracy is rapidly improving. As shown in Table 5, although successive generations of a handwriting recognition algorithm ran more slowly on a given computer, they were more accurate, eliminating many corrections and increasing the overall speed of data input.

Processor chips with more computing ability per Watt are becoming available as silicon technology matures, with miniaturized transistors and wires that enable circuits to operate faster at lower voltages [7]. Increasing scale of integration, enabled both by miniaturization and by increasing the die area (which in turn is enabled by reducing the silicon process defect density [8]) reduces the proportion of connections that must be taken off-chip. On-chip connections have less capacitance[2] than off-chip ones, and so use proportionately less power at a given frequency and voltage swing. The net result of these trends is that the computing ability per Watt has almost doubled every year [9] for thirty years. More able computers will allow the more complex recognition algorithms of the future to run in real time, without requiring more energy.

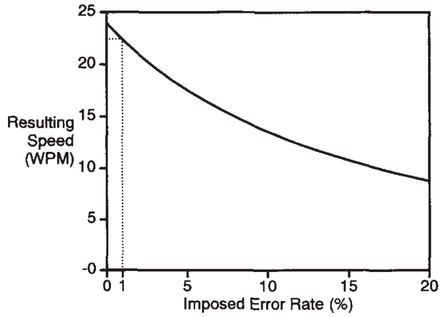

Fig. 4. Effect of imposing random errors on cursive writing speed. In this model, it takes about six times longer to correct a word or character as it does to write a word or character.

Table 5 Comparison of Two Beta Versions and the Production Version of Cursive Handwriting Recognition Software[a]

Version	Release Date	After Correction	Before Correction	
		Rate[b] (wpm)	Word Error Rate[c](%)	Rate[d] (wpm)
0.62	Aug. 1993	12.9	19.7	139
0.75	Dec. 1993	16.2	8.0	108
1.0	June 1994	16.6	7.7	107
Theoretically Perfect		23.8	0	∞

[a] "Longhand" by Lexicus acting on "ink" data in Go Corp.'s "MiniText" under PenPoint 1.01 H release 2B on an AT&T EO880, with 30 MHz Hobbit

[b] Writing, translation, and editing errors to perfect text

[c] All words in the corpus were in Longhand's dictionary

[d] Translation phase alone

V. SUMMARY AND CONCLUSIONS

Personal communicators weighing only ~ 12 oz, yet capable of a whole day of use between recharging, are on the horizon. Once the display and user interface technology are refined and a broad range of application software and services becomes available, these devices will become

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[2] From geometrical considerations, the ratio of on-chip to off-chip connection capacitance is about the same as the ratio of the bond pad pitch (150 μm) to the circuit board pitch (500 μm). This favors monolithic integration and possibly multichip modules.

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