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Networks for Education at the University of Waterloo

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DRAFT

ABSTRACT

Students and faculty members at the University of Waterloo have been using powerful microcomputer workstations connected to local area networks (LANs) since 1981. These workstations support a large percentage of the educational computing in all academic areas of the university. There are over 30 LANs throughout the university and each LAN connects together a number of workstations, file-servers and print-servers.

Originally each LAN was isolated and devoted to computing in a specific group of academic disciplines. Recently the LANs within the University of Waterloo have been interconnected using an extended LAN, thus permitting more sharing of facilities than in the past, since students are now allowed access to their files from any workstation on the campus.

Project ARIES has been started to investigate further refinements of this computing concept. Some groups of students are now being equipped on an experimental basis with portable computers with 512K of memory; these computers can be carried easily between classes. Students can fill their portable computers with software and data from Transaction Ports on a campus-wide LAN and then do their computing whenever and wherever it is convenient. It is expected in the future that this mode of computing will handle a large percentage of the computing tasks normally encountered in an undergraduate program.

This paper describes Waterloo JANET and WATSTAR the two workstation and LAN systems which were developed to form the backbone of the educational computing networks at the University of Waterloo. Reference is also made to the economic and academic advantages of microcomputer workstations connected by LANs. The rationale behind Project ARIES, the current experiments with lap portable computers, and the underlying LAN structure are also described.

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INTRODUCTION

Faculty and staff members at the University of Waterloo have been developing and using computer systems to support education since the early 1960s. These activities have included the development of systems and applications software, and computer systems to make this software accessible to the student body. Such computer systems are often called delivery systems since they "deliver" useable computing power to the students.

A decision was made in 1979 at the University of Waterloo to use microcomputer workstations interconnected with local area networks (LANs) as the next generation of delivery systems for educational computing. The first such system became operational in 1981, and has expanded so that there are now over 30 such delivery systems around the campus serving various academic areas. Each LAN interconnects a number of microcomputer workstations and a network controller. The controller provides access to both systems and applications software and file and print services for each user. These distinct delivery systems are also being interconnected using a LAN so that students can access their own files and other materials from any workstation location on campus.

Project ARIES has been started to examine further refinements of this computing concept with an investigation of the potential of portable microcomputer workstations as general-purpose productivity tools in education. Currently a number of students are being issued with lap portable computers; these computers have 512K of memory and can be carried easily between classes. Students can fill their portable computers from Transaction Ports on a campus-wide LAN, disconnect, and then do their computing at any convenient time and location. It is expected that this mode of computing will handle a large percentage of the computing tasks normally encountered in the undergraduate curriculum in the near future.

This paper describes the evolution of the educational network system at the University of Waterloo and its current operational status. A brief description of the University of Waterloo and its educational computing environment are presented. This description is followed by a comprehensive presentation of the both the form and use of LANs at Waterloo, and an overview of the current research being conducted as part of Project ARIES.

THE UNIVERSITY OF WATERLOO

The University of Waterloo was founded in 1957 in Waterloo Ontario Canada, it was initially an engineering school but quickly evolved into a full-fledged university. Currently the University has a population of 20,000 students spread among six faculties or schools; these are Engineering (3,400), Environmental Studies (1,400), Humanities and Social Sciences (3,000), Human Kinetics and Leisure Studies (1,100), Mathematical Sciences (3,600), and Science (1,200) where the figures in parentheses are the current full-time enrollment in each of these units. There are also 6,000 part-time students who are enrolled across the entire University.

The University of Waterloo is a public university in that it receives most of its operating budget of $120,000,000 from the government. The University also has a substantial research program involving both government and industry with a total budget of $35,000,000.

Because of the era in which it was established and the foresight of the founders, a serious and long-term commitment was made to the use of computing in education at the University of Waterloo. For this reason, almost all the students graduating from the University of Waterloo have completed several courses where the computer is used as a practical tool. As well, almost all the faculty and staff members are knowledgeable about computers and use them in their teaching, research and administrative activities. In other words, almost all students and faculty at the University of Waterloo are computer literate.

THE EDUCATIONAL COMPUTING ENVIRONMENT

A large number of mainframe, mini- and microcomputers are used throughout the University of Waterloo to support many of the educational programs. They are used as tools in a wide variety of activities ranging from the traditional programming of Computer Science through text processing, data base access, simulation, symbolic mathematics, and various forms of electronic communication. Computer resources are usually assigned to courses at the request of the instructor and course enrollments can vary from a few students to more than a thousand.

Most courses which use the computer require the students to have access to teaching materials in a machine-readable format for subsequent exercises and problems. Providing these materials becomes a serious issue in a course where many students are using microcomputer workstations. If "traditional" methods of distribution with diskettes are used, then any errors which are discovered in the materials during the course will often require that all diskettes be returned for correction; in a course with a thousand students this becomes a horrendous management problem.

Some method of distribution is required which allows students to copy machine-readable materials quickly and easily any number of times, and which also provides a simple means of communication between the teacher and the student. Acquiring "correct" versions of the materials becomes the responsibility of the individual student rather than a management problem for the teacher. Such considerations lead to the development of LANs containing some form of file storage to interconnect the microcomputer workstations at the University of Waterloo.

LANs also provide many other advantages which are discussed in a later section of this paper.

LANS AS DELIVERY SYSTEMS

The LANs developed at the University of Waterloo were devised as delivery systems to provide convenient access to software, storage, and printing facilities for students using powerful microcomputers. A LAN consists of a network controller which is a microcomputer, and a communications mechanism which connects the network controller to a number of microcomputer workstations, and file-storage and printing facilities. The communications mechanism is usually some combination of hardware and software which corresponds to the data-link layer in the OSI model of a computer network, [16], [18]. The file storage and printing facilities are usually called file-servers and print-servers.

The network controller operates the network; it provides operating software to each workstation as the workstation is turned on, and helps to route and control the data traffic on the network. At least one file-server and one print-server are also connected to the LAN. A file-server consists of one or more hard disks connected to a microcomputer; the microcomputer runs software to communicate with the network and to manage the files stored on the disks. The print-server has at least one printer also connected to a microcomputer and it runs software to allow files to be queued for printing, so-called print-spooling. The file-server and print-server are often run on the same microcomputer as the network controller. A typical configuration is shown in Figure 1, where the network controller is shown with a printer and disk attached. The microcomputer workstations (labelled WS in Figure 1) are shown connected to the network controller by a communications mechanism represented by the line.
Two LAN systems called Waterloo JANET and WATSTAR have been developed and are in use at the University of Waterloo. Functionally these two networks offer similar services, and so only the details of Waterloo JANET will be described in the remainder of this paper.

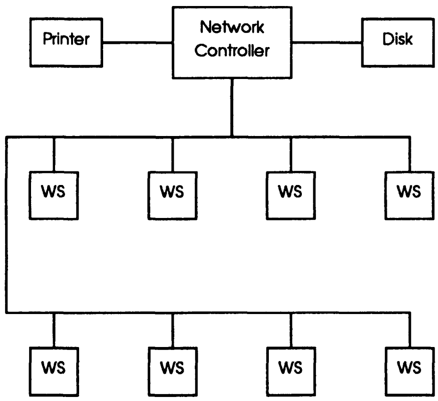

Figure 1. A Local Area Network Configuration

Waterloo JANET

Waterloo JANET follows the generic description presented in the previous section, except that the workstations are usually IBM Personal Computers or equivalent with at least 256K bytes of memory. The workstations may also have diskette drives and will use the operating system PC/DOS. When a user switches from a stand-alone micro-computer workstation to a network workstation, the extra learning required should be minimal; Waterloo JANET was designed with this philosophy in mind.

When a user first sees a microcomputer workstation connected to Waterloo JANET, there is a logo and a line requesting a userid; when the userid is typed a password is requested. Once this sign-on procedure is complete, the Waterloo JANET workstation appears to the user as a normal stand-alone microcomputer with 4 to 6 fixed-capacity network disks. These network disks behave as if they were diskette drives; for example, on an IBM PC the network disks are labelled A,B,C,D,E and F and each can store files in a tree-structured file system. Each network disk can be a different size ranging from 20Kbytes to 1.2Mbytes, the size depends upon some initial allocation. Of course each network disk is actually a portion of the hard disk which is attached to the file-server. The network disks are often segregated by function, for example, there is usually at least one network disk for system software, one for application software, one for course-related materials and one for user files. A typical configuration as seen by a user is depicted in Figure 2.

Security is extremely important when file space is shared among many users in a computer system designed for educational applications. Access to files is controlled by the userid and password required when a user signs on to the system. Also the teacher needs to be able to control the amount of sharing that occurs among the different student user-groups. Waterloo JANET contains mechanisms which allow limits to be placed on this type of activity.

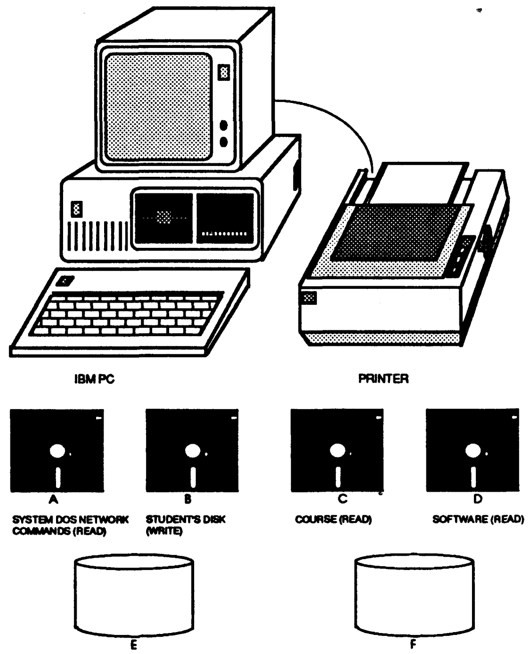

Figure 2. A User View of Waterloo JANET

The communication requirements for a LAN vary with the number of workstations and the type of applications to be supported. Waterloo JANET is designed so that different communication mechanisms or Data-Link Layers can be substituted to alter the speed of the network. Waterloo JANET supports several different Data-Link Layers including PC Cluster (CSMA/CA), PC Network (IEEE 802.3 and 802.2), Token Ring (IEEE 802.5 and 802.2), and IEEE 488, [11], [12], [13], [14], [7].

Almost everything else on the workstation is the same as if it were operating in standalone mode; the operating system (PC/DOS) and all its commands and all the software are still available in the network environment. Some extra commands have been added to provide the JANET environment, but most of them do not need to be learned for "normal" operation of the workstation. The extra commands in JANET allow manipulation of the file-server and print-server. These commands which are described in the following paragraphs are: Access, Detach, Limit, Logoff, Printit, Pswd, Purge, and Qpm.

The access command allows the user to connect one of the labels A,B,C,D,E or F to a new network disk thus making it accessible to the user. Access to a specific network disk may also require a password. The network disk which was formerly attached to that label is not available unless acquired with another access command. The detach command is the opposite of the access command, it makes a named network disk unavailable. These same two commands also allow the use of a diskette drive which may be attached to a workstation or file-server.

The print-server is controlled by a number of commands. The command "printit" is issued by the user whenever printed output is required. "Printit" causes all the printing which has been accumulated or spooled for a specific user to be printed on one of the printers attached to the print-server. The number of characters of printing which can be accumulated by the print-server for any workstation is limited by the size of the buffer. "Limit" is a command which can be used to change this value. Sometimes a program can run amok and produce output which does not make sense; "purge" allows the user to destroy this output without printing it. "Qprn" allows a user to determine the status of the printer; this command will report the number of files to be printed in the queue and the total number of characters in those files.

"Logoff" disconnects a user from Waterloo JANET and from the files that were being accessed, and thus prevents a user from doing any computing. "Pswd" allows the user to change the logon password.

Networks of Waterloo JANETs

Waterloo JANET LANs are dispersed over the campus of the University of Waterloo in different areas corresponding to groups of academic disciplines. Since the computing loads may vary in each area over the teaching term, it would be desirable if students could use any microcomputer workstation on the campus, and not just those assigned to their specific discipline or course. Such a situation would provide significant benefits, since a student would have access to more microcomputer workstations, and all the computing resources connected to Waterloo JANET could be used more efficiently.

Recently, it has become possible for students to use most microcomputer workstations on the campus. Individual Waterloo JANET Networks which are called domains in the rest of this section, have been interconnected to form a larger local area network. A student now signs on to a Waterloo JANET workstation and names the file-server and domain where the student's files are stored. With this extra piece of information it is possible to route data and software between the microcomputer workstation and the file-server.

This interconnection is achieved by designating at least one of the microcomputer workstations on each domain as a communications-server; the network controller can perform this function. Communication-servers in each domain are interconnected so at least one complete path exists between all pairs of microcomputer workstations. The communications-server also contains enough routing information to allow communication with a workstation in another domain.

Waterloo JANET and WATSTAR - Some Experience

Versions of Waterloo JANET and WATSTAR were first installed at the University of Waterloo in 1981 and at the time of writing there are 32 such networks in use, 25 Waterloo JANET networks and 7 WATSTAR networks. As well, about 400 Waterloo JANET systems have been installed in educational institutions and businesses around the world.

Waterloo JANET is used in all the academic areas of the University except Engineering; WATSTAR is the predominant network in Engineering. As well, Waterloo JANET is used by a number of the administrative units of the University. There are currently several thousand accounts on Waterloo JANET and WATSTAR, and the total amount of disk storage available on all the LANs exceeds a gigabyte.

The applications supported encompass almost all academic disciplines and only types of applications can be listed here. Many of the specific applications are quite novel and have been described in separate publications and notes. Programming, data base applications, text processing, simulations, computer-assisted instruction, computer-aided design, graphics and data analysis are some of the areas in which microcomputer workstations play a significant role. Many of the applications are developed by the teachers and their students using standard microcomputer software packages such as interpreters and compilers for programming languages, text processing systems, data base systems, spreadsheets and graphics packages.

MICROCOMPUTER WORKSTATIONS AND LANS - SOME ADVANTAGES

Standalone microcomputer workstations have many advantages over shared mainframe computer facilities when used in an academic environment. When these same microcomputer workstations are further enhanced by interconnecting them with LANs to file-servers and print-servers to allow sharing of facilities, the combination provides even more benefits. Some of these benefits have been described in previous sections of this paper to motivate the original reasons for choosing microcomputers interconnected by LANs. These advantages which can be divided into economic and academic categories, are presented in more detail in the following sub-sections.

Economic Advantages of Microcomputer Workstations

Microcomputer workstations are inexpensive; a number of students can be scheduled to share a single microcomputer over a fixed period of time, thus reducing the cost even more. Adding capacity to a mainframe computer facility through incremental modifications to equipment can be expensive; often the increment adds far more capacity than is required at the time. Buying a microcomputer to add that same capacity is quite inexpensive since the increments are smaller, thus more closely matching the requirements.

Current microcomputers are designed to be modular, and hence easy to expand. Memory is readily added, ports which allow addition of various devices such as a printer, a mouse or a modem can often be incorporated into the microcomputer in a matter of minutes by people with minimal computer or electronics skills. Most of these additions are also inexpensive.

Many of the microcomputers available today are quite durable and require very little maintenance, even when situated in a heavily used student computing laboratory.

Academic Advantages of Microcomputer Workstations

Microcomputer workstations are powerful computers, which because of their low cost, do not need to be shared simultaneously among several users. Since there is no sharing of facilities, response is consistent; a fact which is not true with shared mainframe computers where the response can vary with the number of simultaneous users.

Microcomputer software can all be designed so that the user has the ability to interact fully with all computational activities. This fully interactive computer system is a consequence of the high speed communication link between the microcomputer and its screen and keyboard. This interactive capability lets the student develop solutions to problems in incremental steps, a very effective and natural way to learn.

Microcomputers also have enhanced input/output capabilities which make a microcomputer an excellent tool for education. The old adage "a picture is worth a thousand words" is applicable to microcomputers since most of them have colour graphics and enough computational power for some animation. Also most microcomputers have some capability to create sounds thus adding to the academic value.

Because of the popularity and power of contemporary microcomputers, software developers have created numerous powerful systems and applications software packages which are user-friendly. Teachers have often found many of these software packages easy to learn and use, and have developed many specialized educational packages tailored to specific disciplines.

Economic Advantages of LANs

Since LANs allow sharing of peripherals such as hard disks and printers, there is no need to purchase hard disks, diskettes or printers for each individual microcomputer workstation. Hence, more funds can be directed toward higher quality peripherals, and more function can be provided at a lower cost per student.

Peripherals usually have some mechanical components, and since mechanical devices tend to fail more frequently than electronic ones, fewer peripherals should mean lower maintenance costs. These lower costs are seen in two ways, lower frequency of repair and a smaller inventory of replacement parts.

In a LAN-based system, diskettes are not normally used for storage of student programs and data, or for the storage of most system, application and course-related software. Hence there is almost no need for diskette drives in a network system such as Waterloo JANET. Software is distributed by making it available on the file-server and student programs and data are stored on the file-server. Hence there is no need to purchase diskettes for storage and no need to duplicate and distribute diskettes containing software.

Since diskette drives are not normally available on a microcomputer workstation connected to Waterloo JANET, the risk that users will copy proprietary software, is minimal. Software distributors feel more comfortable with this method of protection against software piracy, and will often grant a network software licence to a network operator. Network software licences usually are a much less expensive way of purchasing software than buying the equivalent number of individual copies.

Academic Advantages of LANs

Centralized storage of software and student data on a file-server provides many academic benefits.

System and application software and course-related materials can be provided and maintained easily. If any of this information needs modification then only one copy has to be changed for an entire class, and students make a personal copy when necessary. In contrast if diskettes were used, then a new set of diskettes would have to be duplicated and distributed to every member of the class, an extremely difficult task. This benefit was mentioned earlier in the paper as one of the reasons for developing a LAN-based system.

Since distribution of machine-readable materials is quite easy with a network, the teacher can now concentrate on development of teaching tools and techniques using the computer. Instead of preparing several months in advance, because of the time necessary to test, duplicate and distribute new materials for large classes, it is now possible to prepare and distribute new exercises and other machine-readable information within a few hours of conception. Teaching can become more spontaneous, since the teacher is not bound to a schedule determined months in advance by the timing of exercises which had already been prepared. Even errors in these materials are not serious, because distribution of corrected information is no longer a problem. Teachers could also easily provide sample solutions and special test data over the network. A problem situation can become much more dynamic with this flexibility and ease of response.

Electronic communication of various types is facilitated with a LAN and microcomputer workstations. Electronic mail between students or between students and teachers, and bulletin boards to broadcast important information, are facilities which are easily available. Conferencing systems where all users can post electronic notices for anyone's response are other useful communication tools. Electronic marking can also be implemented whereby students submit electronic copies of assignments to the teacher's files.

The LAN also contains a file-storage mechanism making it possible to offer file-storage facilities to the students. Students do not have to be responsible for the management of their personal data, a situation fraught with disaster; instead a student's files can be managed by the professionals responsible for operating the LAN. Even if a student deletes the only copy of a file, periodic backups would be available to help the student recover, thus avoiding a personal academic disaster. Also by providing this file-storage facility the need for local file-storage in the form of hard disks or diskettes at the workstation is eliminated.

RESEARCH IN EDUCATIONAL COMPUTING ENVIRONMENTS

Project ARIES - The Portable Computing Project

There are a large number of microcomputer workstations at the University of Waterloo interconnected by LANs, and these provide an effective educational computing environment. However, every system has limitations, and as computer and communications technologies evolve, research should be conducted to make both quantitative and qualitative improvements in educational computing systems.

In the next few sections the current educational computing environment at the University of Waterloo is compared with an "ideal" environment, and the problems of reaching this "ideal" situation are described. Networks and associated services are being designed and implemented to experiment with the form of this "ideal" environment, and both the network and the experiments are presented.

The Current Environment

As mentioned in an earlier section of this paper, computing resources at the University of Waterloo are assigned to courses at the request of the instructor. The amount of computing resource is determined by the type of course and the number of students enrolled. To ensure equal access to these resources, students use a computerized reservation system to request a specific time-period in which to use a microcomputer workstation.

Even though the University of Waterloo has substantial resources dedicated to educational computing, these restrictions are necessary, as there is still not enough equipment to satisfy the demands of the teachers and students. In fact these demands will only come close to being satisfied when there is at least one microcomputer workstation for every student at the University.

The type of course also determines the software which will be made accessible. For example, a course in programming will only provide language processors; normally text processing systems, data base systems or spreadsheets would not be made available. This restricted set of software limits the student's computing activities to those prescribed by the course, and hence restrains the student from "wasting" limited computing resources. In other words, a student in a programming course would not be able to use a word processor to prepare an essay or report for another course, unless that specific course also had access to computing resources. This unfortunate situation is caused by limited resources.

Although the University of Waterloo has substantial computing resources, they are still inconvenient to use. Microcomputer workstations are in fixed locations and so the user must travel to the computer rather than having it available at all times in a manner similar to a book, calculator, or pencil. For most tasks there is a tendency to choose the tool that is most readily available, and since computers are often not conveniently accessible they are often not used, even though they may be ideally suited for the current activity.

Even when computing resources are available and accessible there may still be problems. The human interface on the microcomputer may not be the one with which the student is familiar, and so the microcomputer is not useable. For example, there is excellent software available under different operating systems such as PC/DOS or Unix and different teaching areas may choose different operating environments. Students should not be expected to be knowledgeable about more than one such environment.

The "Ideal" Environment (Computing on Demand)

The computer should be a commonly used educational tool, as available and accessible as the calculator is today. Computing should be available on demand to all teachers and students in the university irrespective of the subject area. The next sections explore how ***computing on demand*** might be provided by examining possible strategies.

Since lack of computers seems to be central to providing the ideal computing environment, perhaps the simplest solution would to purchase one microcomputer workstation for each student. What are the implications of such an action? Before making this decision a number of factors should be considered including: cost and obsolescence, space requirements, inconvenience, the user interface, and physical requirements such as power, air-conditioning, maintenance and communications. These factors are examined in the next few paragraphs.

Approximately twenty thousand (20,000) microcomputers would have to be purchased to satisfy the demand at the University of Waterloo. If the cost of these machines was estimated at $2,500; then the total cost would be $50,000,000. This number of microcomputers would also require a substantial amount of new space. Conservatively estimating a space requirement of twenty-five (25) square feet (2.3 square meters) per microcomputer means constructing a building of 500,000 square feet (46,000 square meters). With construction costs of $100 per square foot the building would cost $50,000,000. Hence the total cost for this type of educational computing facility would be $100,000,000, almost the entire annual operating budget of the University of Waterloo. Obsolescence also would be a factor, since these microcomputers would probably have to be replaced every three (3) to five (5) years.

Even if the microcomputers were purchased, there would still be the problem of inconvenience, since they would be fixed in location. A computer would often not be available when and where it was needed. Also since computers in different locations would tend to be dedicated to different functions, the user interface could vary across the University.

Finally the physical requirements of installation such as power and air conditioning could add to the initial cost. Although microcomputers are quite robust, there would still have to be a substantial initial investment in maintenance staff, equipment and training to establish a repair facility for 20,000 machines. Communications in the form of networks would have to be installed if the level of functionality currently available at the University of Waterloo were to be maintained.

Is there any hope of finding a solution to this problem of supplying ***computing on demand***? The next section examines a possible solution and analyzes it in terms of the parameters already discussed.

A Dream or Potential Reality?

Inconvenience, even with the introduction of the microcomputer, is still a serious impediment to widespread use of computer technology in education and many other fields. If a computer was truly portable and could be easily carried, and had easy access to software and data, then lack of convenience would no longer be an important factor.

A dream for the long-term, similar to Alan Kay's Dynabook [8], [9], is that every student at the University of Waterloo and at other educational institutions will carry a fully functional portable computer, and will be able to compute wherever and whenever the need arises. Such a portable computer should have the following properties, it should:

i) be very light in weight, weighing under a kilogram;

ii) have a large memory of at least 2,000,000 bytes;

iii) have a colour graphics screen with the capacity of a standard sheet of paper;

iv) be solar-powered;

v) be as compact as a regular-size three-ring notebook;

vi) have an extensive suite of software available;

vii) be able to store and retrieve software and data using a high-speed wireless network;

viii) and be inexpensive enough that a student could afford to buy such a computer over a period of about 4 years (currently this appears to be a price of about $2,000).

When such a computer becomes available, the student will not go to the computer, the computer will be with the student.

Although this is only a dream at the moment, such a dream is not that far from reality. Portable computers with specifications quite close to the ideal computer just described can be purchased. Such machines

i) weigh approximately 4 kilograms;

ii) have a memory of 500,000 bytes;

iii) have a monochrome graphics screen, 80 characters in width and 25 lines in depth;

iv) are operated by batteries lasting 10 to 20 hours;

v) are as compact as a large three-ring notebook;

vi) have some software available;

vii) have a medium-speed connection to a wired network;

viii) and cost between $2,000 and $5,000.

Truly portable computers will have a significant impact on a number of the parameters already discussed. Since the computers are portable and remain with the student, space, power and air conditioning will no longer be a problem. Convenience has already been discussed, portability will make the computer as accessible as the calculator. Each student will be able to tailor the user interface on their own portable computer to their particular requirements.

Four issues, namely cost, obsolescence, maintenance, and communications still need to be resolved. The next section of this paper examines the communications structures needed to support portable computers. A subsequent section describes how the resolution of the communications issue will affect cost, obsolescence and maintenance.

Communication Structures for Portable Computers

Since the users of portable computers will require access to many different software systems, general and personal data files, and communications facilities, some mechanisms must be established to distribute this material efficiently. Although diskettes are one such method they also introduce a level of inconvenience which mitigates against personal computing use; students and faculty must still obtain their materials from a central source by what might be termed "manual" methods.

Electronic distribution of software and data through high-speed communication networks seems to be the answer, as such networks would provide instantaneous availability. As well networks would provide access to graphic output services such as high-quality or high-speed printers, typesetters and plotters. File storage could also be a service supplied through the network.

Of course not all computing services required by students and faculty in an educational institution can be supplied by portable microcomputers. For example, it is likely there will be software systems which will require the resources of a large mainframe computer no matter how large the microcomputer becomes. For this reason portable microcomputers must have the capability of connecting to mainframes through a network.

The network would be all pervasive much the way the telephone network is today. The network would be accessible in all areas of the university including the classrooms, laboratories, library, eating areas, study areas, and the residences. Eventually networks would be accessible in the surrounding community, other cities, and eventually remote locations.

Unfortunately networks are not always accessible nor do the current networks have the capacity to handle the amount of data traffic which is usually encountered in a university environment. As well as high-speed wired networks, experiments will have to be conducted with wireless networks which might use radio, cellular telephone and even satellite communication.

Experiments with networks for portable computers are being conducted at the University of Waterloo and are described in subsequent sections of this paper.

Solving One Last Problem

A method of resolving the issues of cost, obsolescence and maintenance have not yet been addressed in this paper. This section contains a discussion of these issues and how they could be handled in the context of portable computing.

Based on past experience with microelectronics, the cost of portable computers should decrease to less than $2,000 in the near future; current prices of some models are already close to that figure. Surveys of students have indicated that they would be willing to buy a portable computer, if the price was about $2,000 and if the computer could be purchased over a period of four years (the normal time to complete an undergraduate degree).

Of course students will only buy portable computers if they perceive that the network services to support the computers are adequate, and if the convenience of use outweighs the capital cost. The electronic calculator already provides an example of a convenience-versus-capital-cost trade-off. When calculators were expensive, laboratories were equipped with calculators and students went to these rooms to do various scientific computations. As the price of calculators decreased, students sacrificed capital for the convenience of possessing their own calculator and being able to do their computations when and where it was convenient.

A similar argument applies to portable computers. If the cost is low enough (less than $2,000) and the network and support services are adequate, then students will buy a portable computer. The capital cost of computing will be transferred to the student, the consumer of education. Obsolescence of this type computing equipment will no longer be an issue, since the University will not have the responsibility of replacement. Maintenance of course is the responsibility of the owner of the equipment, although the University could make this service available for a small annual fee. Such a fee could also include rental of a replacement computer while the student's computer was being repaired.

A Network for Portable Computers

Experiments with networks and network services for portable computers have been conducted at the University of Waterloo since 1984. The next sub-sections provide details of the computers being used, the user interface and services provided, the current network, and future plans for the network. A diagram depicting the current network configuration is shown in Figure 3. As the network evolves it is expected to support a wide-ranging heterogeneous educational computing environment.

Since the portable computers are supported by network services, they can more accurately be described as portable workstations and this term will be used in the rest of this paper.

The Portable Workstations: The current experiment is using 310 Hewlett Packard Portable Plus Computers and 40 IBM PC Convertibles which are distributed to various student groups around the University.

The Hewlett Packard Computers have 512K bytes of memory, a 25 by 80 monochrome screen, and weigh about 4.5 kilograms. The operating system is MS/DOS 2.1. These computers do not have a built-in diskette drive, and so usually half the memory is configured as an electronic disk. This computer also has two communication interfaces, an asynchronous communication port and an HPIL interface. The HPIL interface is similar to a serialized version of the GPIB or IEEE 488 protocol [7]. and can transmit and receive data at about 10K bytes per second.

The IBM Convertibles have 512K bytes of memory, a 25 by 80 monochrome screen, 2 720K-byte, 3.5-inch built-in diskette drives, and weigh about 5 kilograms. PC/DOS 3.2 is the operating system. This computer also has an asynchronous communication port as its communication interface and by suitable programming the interface can transmit and receive data at about 5K bytes per second.

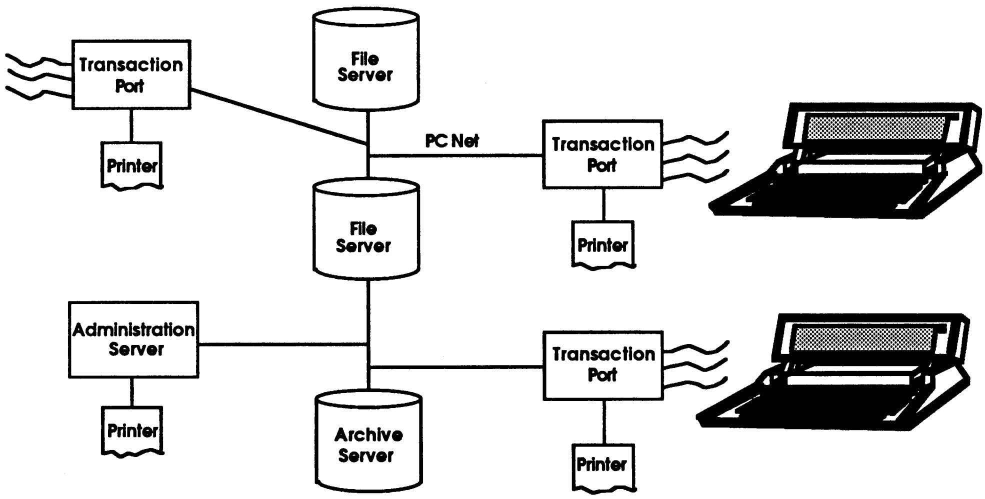

Figure 3. Project ARIES Network Configuration

The User Hardware Interface: There are currently eight (8) Transaction Ports on the University of Waterloo campus where users can obtain services. These Ports are at widely distributed points around the campus within an area of approximately 150 acres (61 hectares).

Each Transaction Port consists of a complete microcomputer with a keyboard, a screen, a printer, and a system unit containing 512K bytes of memory, an Intel 80286 CPU and both a 5.25 and 3.5 inch diskette drive. As well, the system unit contains an adapter card for a network connection and a number of adapter cards with attached cables for both asynchronous (RS232) and HPIL communications.

Users may take their portable computers to a Transaction Port to transfer data between the Port and the computer. This data may then be either transferred into the network or displayed on the printer attached to the Port. Users who have computers which are not portable may bring a diskette to the Port and obtain the same services.

A user approaches the Port, and either attaches the portable computer to the adapter cards using the cables or inserts a diskette into the diskette drive. Services are then obtained by using the keyboard and screen attached to the Port. From the user's perspective the Transaction Port is similar to a banking machine; the user plugs in the portable computer, provides identification, and obtains a number of services.

The next section describes the services currently available to the user through the user hardware interface.

The User Software Interface and User Services: After connecting the portable computer or inserting a diskette, the user obtains services by activating commands which appear as menus on the screen at the Transaction Port. These menus define the services that are currently available from the network. These services include: authentication and authorization, file transfer (including electronic mail and printing a file), directory access and maintenance. A description of some of these services is presented in the next few paragraphs.

The authentication service is similar to the logon procedure on any shared-resource computer system. Execution of a logon command with a userid and password authenticates the identity of the user, and authorizes access to the user's file space. Once access to the file space is permitted, other services such as accessing other file spaces, become available. These additional services may also require a second level of authorization.

The current file space provided to the user is identical in appearance to any MS/DOS or PC/DOS file system. A user has access to a number of directories (labelled A:, B:, C:, D:, E: and F:), each one of which supports a tree-structured file system; these directories emulate the diskette structure of the MS/DOS file system. Even though the underlying file system is totally tree-structured, the extra level of structure is imposed to provide transparency to the users of the current portable computers. There is also an archive system which provides for file backups. Periodically the archive system checks all file spaces and copies any files which have been changed since the last archiving operation. The archiving system thus allows recovery from either a system failure or an inadvertent user error.

The mail system must provide for the fact that the portable workstation is not always connected to the network. All outgoing mail is placed in an out-basket in the workstation's local file-space, and when the workstation is connected to the network the mail in the out-basket is sent and any incoming mail is placed in the workstation's in-basket. This system allows the user to process mail while disconnected from the network.

Administering the Network: One workstation is permanently attached to the network as an administrative-server. Functions such as the operation of the archive-server, and the creation, deletion, or renaming of accounts and directories are usually performed from the administrative-server. All these activities can be performed while the network is fully operational. The administrative software is only available in the administrator's file space, and requires authorization through a password before use.

The Current Underlying Network: The current Project ARIES network consists of eight Transaction Ports, two file-servers with a total of 80M bytes of disk storage, an archive-server, and an administrative-server. The Ports and the servers are interconnected with Physical and Data-Link Layers consisting of PCNetwork running on a coaxial cable. The network can also contain gateways which allow the interconnection of several LANs, although no gateways are installed at present. The remainder of the description of the Project ARIES network will be loosely based on the Open System Interconnection (OSI) Model [17], [18].

PCNetwork is a broadband network using a carrier-sense multiple-access collision-detection protocol (CSMA/CD) [13]. The interface between the Network and Data-Link Layers is designed so that the Network Layer is independent of the Data-Link Layer. This independence feature allows different Data-Link Layers to be used in the Project ARIES network without affecting any of the software running in the upper five layers of the network (Network, Transport, Session, Presentation and Application). Although the Project ARIES network is currently using PCNetwork for the Physical and Data-Link Layers, other network types such as Token-Ring [14], have been substituted on an experimental basis and have operated quite successfully.

Each Transaction Port, server and gateway runs a kernel containing a real-time scheduler, so that the software on these computers may be process-based. The processes communicate by passing messages and use a model similar to the one used in Thoth [2], [4], MINIX [17], or V kernel [3]. The next few paragraphs describe how a message is sent between a sending and receiving process.

For a sending process S to send a message to a receiving process R, S must know the entire address of R, and R must be running on a computer in the network. The address of a process consists of three parts: the domain, node, and port on the network. Each domain represents the address of a LAN interconnected to the network by a gateway, a node represents the address of a workstation or server in a domain, and a port is the address of an individual process in a workstation or server. Normally, a sending process S in the Application Layer communicates with a receiving process R in two steps:

i) the sending process S spawns a Transport Layer process P_1,

ii) and S sends a message to the receiving process R by a procedure call with three parameters, namely the name of P_1, the address of R and the text of the message.

Since R is running and expecting messages, it will have spawned a Transport Layer process called P_2 (similar to P_1) which will receive messages sent from S, and any other processes communicating with R.

As messages are sent to P_1 in the Transport Layer, they are divided into packets, the packets are sequence-numbered, the address of the receiving process is appended to each packet, and the packets are then sent to the Network Layer. Upon reception at P_2 in the receiving Transport Layer, the packets are reassembled in the correct sequence, the address is removed, and the entire message is passed to the receiving process. The network currently implements a modified datagram service, since the Transport Layer is responsible for packetizing and re-assembling messages but does not guarantee delivery; the application processes are responsible for re-transmission and acknowledgement of messages.

The Network Layer has a switch process with a static routing table containing information about the domains, nodes, and ports on the network. The switch communicates with a process which passes information to the Data-Link Layer for transmission over the network. A single workstation or file server would only have one such process, while a gateway would have one process for each connected LAN. The process which connects the Network Layer and the Data-Link Layer adds any information needed to send the message over the network, and is the process which must be replaced when a different Data-Link Layer is installed.

Expansion of the Network Services

Since this is a research project on heterogeneous computing environments to support convenient educational computing, there are still many services and network functions which need to be explored. The next few paragraphs present some of the future direction for the Project ARIES network.

Users of text-processing software are beginning to expect high-quality laser-printed output whenever they print a document. For this reason it will be necessary to provide laser printers at each Transaction Port. However, the cost of laser printing is too expensive to be absorbed in a university budget, and so mechanisms must be in place for users to prepay for printing on unattended laser printers. Experiments are being conducted with various techniques such as debit cards, and bar-code readers to provide users with a method of authorizing the release of their printing and the charging of their "accounts".

Currently, users of portable workstations only have access to the facilities of the Project Aries network. The University of Waterloo has many other networks such as TCP/IP, DECNET, Localnet 20, and

RSCS which provide access to most of the other computing facilities on campus. In turn, these other networks are connected to various wide-area networks which provide access to world-wide communication facilities. Research needs to be conducted in providing uniform portable interfaces between the Project Aries network and these other networks.

At the present time, users can only access the Project Aries network on the campus of the University of Waterloo. This is a serious shortcoming, since a large number of the students do not live on campus, and the University also supports a very large distance-education program. The Project Aries network will be expanded to support off-campus computing uses; students will be able to access the network through the Datapac system. Students in the distance-education program will also have access to a conferencing system to provide better communication between the faculty and their fellow students.

Experience With Portable Computing

Experiments with the use of portable computers in education were initiated at the University of Waterloo in September 1985. The portable computers have been used in 24 courses including ones in Biology; Chemical, Civil, Mechanical, and Systems Engineering; Chemistry; Computer Science; Environmental Studies; Leisure Studies; and Physics. Varied activities have been undertaken particularly in the area of simulation, text processing, data bases, numerical analysis, programming and logic programming. Translators for languages such as Basic [10], Fortran-77 [6], Pascal [1], and Prolog [5], have been used as well as applications software for text processing [15], and data bases [19].

The response from the faculty and students using the portable computers and the network has been quite enthusiastic. Assessment of the system is determined by random in-depth interviews with the students and faculty and by a detailed questionnaire which is completed by each student at the end of the term in which they participated in the experiment.

SUMMARY

This paper has described the University of Waterloo and its educational computing environment. Waterloo JANET and WATSTAR, the educational computer systems based on microcomputer workstations and LANs and the rationale underlying their development have been described in some detail. LANs allow users of microcomputers to share file storage and printing facilities and hence LANs provide many advantages in educational computing. Distribution of machine-readable materials is simpler and communication among the users offers many benefits.

Computing is still inconvenient because the user must go to the computer, the computer is not always with the user. In the second half of this paper Project ARIES, the University of Waterloo Portable Computing Project, is described in which it is planned to build networks and software so that students at the University of Waterloo may use powerful portable microcomputers (sometimes called lap portables) anywhere on or off the campus and yet have access to extensive software and data, high-speed and high-quality printers, and centralized personal file-storage. The primary function of the network will be to allow students to obtain software and data, to put their completed work into permanent mass storage or onto "hard-copy output devices, and to communicate with their peers and the faculty. The project will initially use wired local- and wide-area networks but as the project progresses it is anticipated that many of the functions will be provided through various types of wireless communication. The combination of portable computers and easy access to various computing services through networks will allow students to use the computer whenever and wherever it would be a suitable tool.

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