A Low Power, Low Bandwidth Protocol for Remote Wireless Terminals

George Hadjiyiannis
Department of EECS
MIT, Cambridge

Anantha Chandrakasan
Department of EECS
MIT, Cambridge

Srinivas Devadas
Department of EECS
MIT, Cambridge

Abstract—**We present a low bandwidth protocol for wireless multi-media terminals targeted towards low power consumption on the terminal side. With the widespread use of portable computing devices, low power has become a major design criterion. One way of minimizing power consumption is to perform all tasks, other than managing hardware for the display and input, on a stationary workstation and exchange information between that workstation and the portable terminal via a wireless link. A protocol for such a system that emphasizes low bandwidth and low power requirements is presented herein. Such a protocol should address the issue of noisy wireless channels. We describe error correction and retransmission methods capable of dealing with burst error noise up to BERs of 10^{-3}. The final average bandwidth required is 140Kbits/sec for 8-bit color applications.**

I. Introduction

Recent years have seen a dramatic increase in the demand for computational resources. The major trend has been for users to demand easier access to computers. Personal workstations have not fully satisfied this need and portable computing has become a focus of considerable attention. Various researchers (e.g., Mark Weiser at Xerox PARC [1]), intend to take this even further until computers are so common place and so much in tune with human needs that their users are not even aware of them. This notion has been termed "ubiquitous computing"[1].

For the moment, portable computing is the only manifestation of ubiquitous computing that has gained any commercial success. While power consumption is becoming a serious concern for the designers of the new breed of ultra-fast microprocessors, it is the field of portable computing that best motivates research into low-power dissipative technology.

A. Factors Affecting Power Consumption

The easiest way of reducing the power consumption of any computing device is to reduce the amount of computation it performs. Power consumption is proportional to $C \times V^2 \times f$ where C is the effective capacitance switched, V is the voltage at which the circuitry operates, and f is the switching frequency. Reducing power consumption involves reducing any or all of the above factors. Reducing C can be accomplished by (a) a more aggressive process, (b) clever circuit design and (c) reducing the number of active computational units. For a given design methodology and process, the only reasonable way of reducing the capacitance switched is by deferring some of the computation to other resources and thus eliminating some of these computational units[1]. Reducing f reduces the rate at which these units operate. Reducing V increases propagation delays which forces a reduction in maximum f [2]. Therefore, any attempt to reduce the power of a computational device by any significant amount[2] will result in lower throughput from that device.

[1]Note, however, that one can opt to use more computational units to offset the reduction in speed caused by reducing the voltage V. This can result in a net decrease in power consumption.

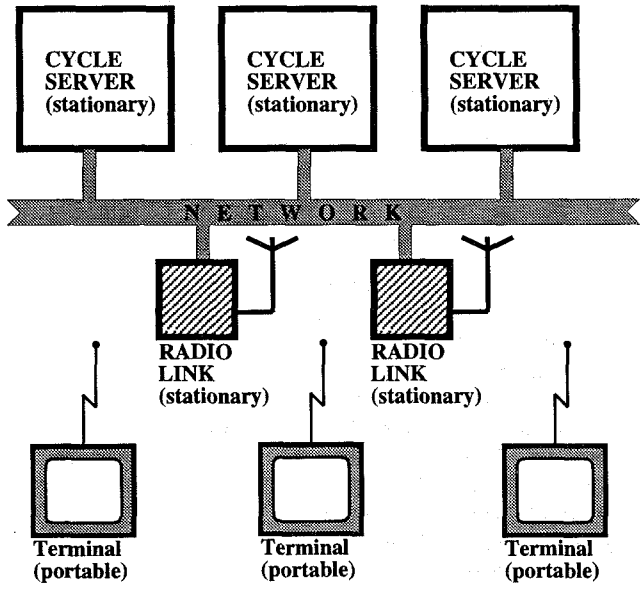

Fig. 1. The stationary cycle server model.

B. The Stationary Cycle Server Model

An interesting way to work around the power/throughput tradeoff has been used by both the Xerox PARC group and the InfoPad group at Berkeley [3], [2]. The portable computer (hereafter called the terminal) can do just enough work to manage the input and output devices and defer all other computation to a separate cycle server (hereafter called the stationary cycle server or just cycle server for short). The terminal and the cycle server can be connected in such a fashion as to allow the terminal to transmit all input to the cycle server and the cycle server to transmit all output back. If the connection method is wireless, then the terminal becomes effectively a portable computer (see Figure 1). Since the cycle server is stationary, it can have an external power source and the only power consumption that the designer needs to be concerned with is that of the terminal. This becomes an easier task since the terminal can be designed to perform the minimal amount of computation necessary to manage the input and output devices. Nonetheless, to the user the terminal appears to have all the processing power of the stationary cycle server.

Under this scheme, all the applications run on the cycle server while the display and input device management programs (e.g., a window server) run on the terminal. Input from the devices is relayed by the terminal through the radio link to the stationary radio station, which then places it on the network. From there, it finds its way

[2]For the scope of the above statement, a significant amount would be something close to one order of magnitude.

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to one of the stationary cycle servers, which processes the input and feeds it to the applications. The applications then inform the cycle server of any impending output (e.g., updates to the display), which is then put in the right format and placed on the network. The stationary radio stations take the properly formatted output and relay it over the radio link to the appropriate terminal. Finally, the terminal decodes the message and performs the appropriate updates or output actions.

C. The InfoPad Protocol

The InfoPad is based on the X-protocol. Rather than running a complete X-window server on the terminal, a new protocol was designed that allowed most of the X-window server tasks to be moved to the cycle server. Thus, raw pen events are relayed from the InfoPad terminal to the cycle server over the radio link, where they are processed by a modified X-window server. The X-server processes the input events as if they came from a local keyboard and mouse and then generates events for the applications. The applications process any input events they receive, and send any necessary output requests to the X-server (just like they would if the X-server was to display it on the local screen). The X-server calculates the necessary updates to the display, packs that information through a special protocol, and relays it over to the terminal. Finally, the terminal unpacks that information and updates the screen accordingly.

One of the main design issues was the nature of the protocol to be used between the X-server that was running on the cycle server, and the terminal itself. Since the main design goal was to make the power consumption of the terminal as small as possible, the protocol was designed such that the hardware requirements on the terminal side were as simple and as minimal as possible. For the first generation of terminals, it was decided to send the full display updates as a series of bits for every pixel that had to be modified on the display. Later generations used enhanced protocols that had lower bandwidth requirements. Note that this description only applies to the text and graphics display. It does not cover the video portion of the output, which used a different protocol to transmit compressed video. We call protocols such as the first generation InfoPad protocol "computationally cheap" since they try to minimize the computation performed on the terminal.

This computationally cheap protocol may cause two problems:

- It requires large bandwidths on the downlink that sends the data from the cycle server to the terminal. It also means that when large portions of the display change (such as the example of putting a large amount of text on the screen), the latency of transferring such a large amount of data becomes the dominant portion of the response time of the whole system. Also the bandwidth requirement would be almost 8 times higher for a color system than for a monochrome one.
- Since the implementation of the protocol was in hardware, it is particularly inflexible, requiring the design and fabrication of new components for every change in protocol that needs to be made. While a fully general approach might not be necessary, some software flexibility would be desirable.

D. Our Approach

This paper represents our effort to extend the work of the InfoPad group. The basic premise of designing a low power terminal by using the stationary cycle server model is still the goal, but having the benefit of all the data collected by the InfoPad group, we decided to use a different approach to the problem. To begin with, we decided to replace the InfoPad's hardwired protocol with a general-purpose processor enhanced with application specific optimizations, at the expense of higher hardware complexity and larger power consumption. Thus, the terminal and its protocol would become relatively flexible, allowing us to make use of better algorithms, new extensions to the X-server, and to make additions and modifications to the protocol at will. Then we decided to employ a more computationally expensive protocol which would reduce the bandwidth requirements and alleviate some of the problems associated with the high bandwidth, while at the same time allow the use of color. The enhanced protocol is the subject of this paper.

II. The Communication Protocol

As described in section I-C, the main reason for moving to a new protocol was to reduce the amount of information that has to be sent on the downlink to the terminal. By giving the protocol the notion of higher level elements (for example, rectangles, polygons, lines etc.), it is possible to create a protocol that requires much less information to perform the same activities. If the protocol had a notion of what a text character is, one would only need to send a command that identifies the character, its position, and the color to which it should be drawn. We decided to give the protocol the notion of such higher level elements to reduce the bandwidth requirements. We also decided to use color, therefore the protocol had to work for 8-bit pseudo-color frame buffers with a 640×480 resolution.

A. The Raw Graphics Protocol

The first step in developing a protocol was to come up with the exact type of requests that would be necessary, and the information that these requests would require in order to allow the terminal to reproduce the display that the X-server is trying to build. Obviously, a big part of this task is simply deciding which higher level elements (and operations on such elements) would be the best to include in the final protocol. This set of requests, elements and operations forms what we call the Raw Graphics Protocol. Given this protocol, it would be possible to make a perfectly functioning terminal that would operate with no errors in the absence of noise. Just like the InfoPad and the Xerox PARC Pads, we decided to base our protocol on the X-window system.

A.1 The Partitioning Issue

The X-server is built with a particularly modular structure that consists of 3 main modules (see Figure 2): On the top level is the DIX layer, or Device Independent layer, and below that are the Operating System layer or OS, and the DDX layer or Device Dependent layer. Each layer consists of sub-layers that exchange information with each other. The most important layer is the bottom sub-layer of the DDX layer, called the Color Frame Buffer code, or CFB module for short. This layer changes the appropriate pixels in the frame-buffer to actually service the request.

A communication protocol for the terminal can be implemented by partitioning the X-server between any two of the layers and intercepting the communication between them, to relay that information to the terminal. By reproducing all the layers below the partition on the terminal side, one can reproduce all the actions of the X-server while servicing the request, and therefore one can reproduce the final display (see Figure 3). That, of course, poses the question of where the partition should be placed. Note that the partition does not necessarily have to lie on sub-layer boundaries. It is also possible (and in fact necessary for optimization reasons) to place the partition at different levels for different parts of the code.

Generally, levels that are higher up have access to more of the basic elements (see section II-A.3) than levels that are lower. However, by placing the partition lower, one can simplify the protocol as well

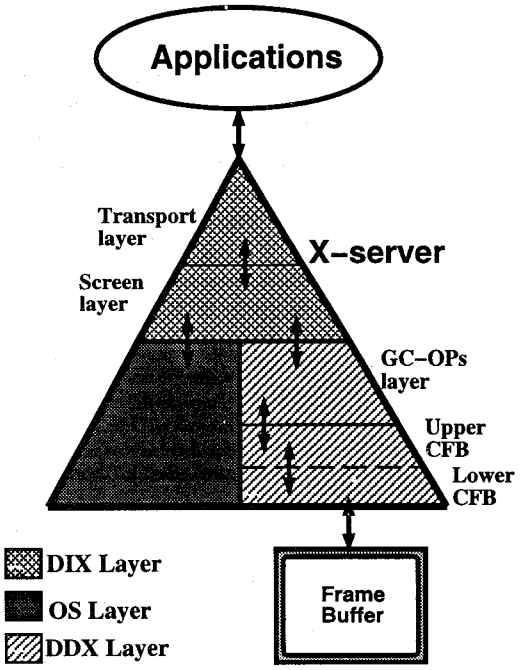

Fig. 2. The internal structure of the X-server.

as avoid performing the work of the higher layers on the terminal. Section II-A.2 explains why avoiding the work of the higher layers is particularly important in maintaining low power consumption.

On one extreme, the partition could be placed on top of the Transport layer. Effectively, this means running the complete X-server on the terminal and running only the applications on the cycle server. This is the approach that was used by the Xerox PARC Pads. This would make available to the protocol all the information that could possibly be available. The bandwidth required for the downlink would be small since all requests would be using higher level elements, and would have available to them all the X-server state. On the other hand, this would place very heavy demands on the terminal hardware (the memory to store said state being a major concern).

On the other extreme, we could place the partition right below the CFB sub-layer and intercept the communication between it and the frame-buffer. Since the communication between the CFB sub-layer and the frame buffer consists of the values of the individual pixels, this is effectively the same as the first generation InfoPad protocol. It has very minimal terminal hardware requirements but suffers from high bandwidth requirements.

For the purposes of the current protocol we decided to place the partition at an intermediate point. While it is true that levels higher than the CFB sub-layer have access to more elements than the CFB layer , the lower levels of the CFB sub-layer have access to most elements that take part in the actual drawing operations. We decided to place the partition within the CFB layer, immediately above the routines that actually perform the drawing operations in the frame buffer (see Figure 3). This lower portion of the CFB sub-layer has all the basic notions of geometric objects that might be drawn on the screen, but lacks the notion of all other elements (such as the notion of windows). For most drawing operations, this means that various pieces of information about higher level elements have to be transmitted every time (for example the position and clip-region[3]

[3]The clip-region is the portion of the window that is actually visible at any given time. Parts of the window might be obscured by other windows.

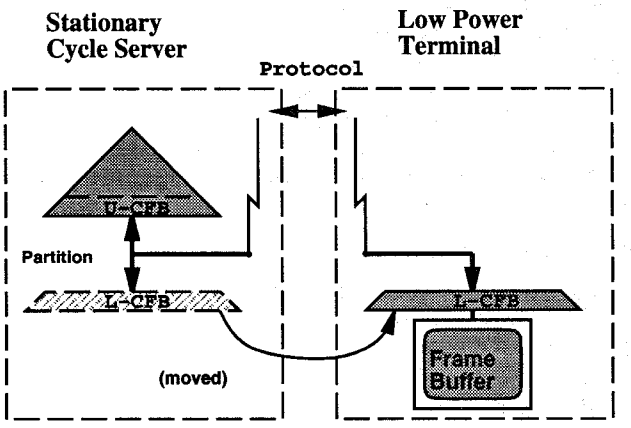

Fig. 3. The partitioning of the X-server to obtain the protocol.

of a window). Generally, this overhead is not significant enough to warrant the extra complexity of a higher level. For some parts of the code (mainly the portions of the CFB code that handle text) we had to place the partition in the higher levels of the CFB sub-layer, since it would provide us with a substantial bandwidth advantage.

A.2 Low Power Issues

The main tradeoff in designing the protocol is between bandwidth and complexity. The main reason why complexity needs to be kept under control is that it affects the final power consumption of the terminal hardware. There are three major parameters that are dictated by the protocol complexity and which affect the terminal hardware power consumption:

Number of Tasks The more computationally expensive the protocol, the more the throughput required, hence the higher the power consumption.

Memory Requirement It is necessary to keep the memory requirements of the terminal to a minimum [4]. Therefore, both the size of the code and the amount of state it needs to save, must be kept minimal. Both sizes tend to be smaller for computationally cheap protocols.

Better Mapping to Hardware If the protocol is particularly simple, with most operations being of the same type, then there is a greater opportunity for architectural optimizations to the hardware. Such architectural optimizations allow a reduction in clock rate (which allows a reduction in voltage supply as well) thus providing very attractive power savings.

A.3 The Element Types and Operations

Once the location of the partition in the X-server was determined, deriving the protocol requests (and hence the element types and operations) was a simple matter of determining what information needed to be relayed to the terminal to reproduce the drawing actions of the X-server. Effectively, all the drawing routines had to be intercepted to make sure that any operations that affect the display are reproduced on the terminal side. Since the partition was placed right above the drawing routines, it was generally unnecessary to save any state for longer than a single request. All the information needed by each drawing routine could be relayed to the terminal for each request. The only exception to the above rule was the caching of fonts – up to 256 fonts can be cached on the terminal side in our protocol.

The basic elements that the protocol is aware of are boxes, lines, arcs, ellipses, chords, pixmaps, regions, text strings, fonts and colormap entries.

The following operations are available to the communication protocol:

Basic X protocol operations [5] The X protocol defines 16 operations by which the new drawing primitive can be combined with the existing contents of the frame-buffer to yield the final image. All 16 are supported by the communication protocol. Some of them are optimized and have their own request identifiers (e.g., the Copy request which overwrites the old contents of the frame-buffer and therefore does not need to read the frame-buffer – only write to it).

Stippling Operations These are operations that use a bitmap as a mask in order to only affect certain portions of the image.

Clipping Operations These are operations that restrict the basic drawing operation to a particular region (that might contain multiple boxes).

Input Operations Five requests are reserved to allow the transmission of user input (e.g. from a mouse or keyboard):

Pointer Motion The user has moved the main pointer (e.g. a mouse or pen) to the new location mentioned in the request.

Button Press The named button on the main pointer was pressed.

Button Release The named button on the main pointer was released.

Key Press The named key on the keyboard was pressed.

Key Release The named key on the keyboard was released.

The above set of elements and operations forms what we call the Raw Graphics Protocol (the fully functional protocol before error correction, detection and retransmission).

B. Error Correction, Detection And Retransmission

The raw graphics protocol is all that is necessary to allow the terminal to work in the absence of any noise. Wireless communication channels, however, are notorious for containing strong noise sources. An unfortunate consequence of making a protocol out of higher level primitives is that its noise tolerance decreases dramatically. In the InfoPad protocol, most of the data represents pixels on the screen. If any of that data gets corrupted, the end result will be that some pixels on the screen will have the wrong color. For our raw graphics protocol, however, a very substantial fraction of the data is control information that dictates the request type, the clip regions, the locations of the primitives, etc. If any of that data gets corrupted, the results could be disastrous. The primitive might be drawn to the wrong place on the screen, it might be clipped severely or even the wrong request might be detected at the terminal side with completely unpredictable results. The raw graphics protocol is therefore particularly ill-equipped to deal with noise.

One possible solution would be to wrap the data in an error detecting code (e.g., a CRC) and then retransmit any requests that were corrupted. However, one of our design goals was to make the protocol work relatively well with Bit Error Rates (BER for short) as high as 10^{-3}.[4] Given the size of some of the requests, the above scheme was likely to result in an unacceptably large number of retransmissions since a large number of requests would have at least one bit corrupted. A better approach would be to use a code that can actually correct many of the errors, thus avoiding the need for retransmission in most cases.

[4]Both the expected noise characteristics and the noise produced by our emulator environment have a large content of burst noise which is a lot harder to overcome than simple random noise.

B.1 The RS(15,9,7) Error Correcting Code

A number of error correcting codes were explored for use in the protocol. The final choice was a Reed-Solomon code that works on 4-bit symbols, encodes 9 symbols to 15, and detects and corrects 3 simultaneous errors[6], [7]. The main advantages of this code are its immunity to burst mode noise and large error detection capability. With two-way interleaving, the shortest burst error undetectable by this code is 22 bits. The code is also relatively small in size, each codeword having 15 symbols, i.e., 60 bits.

B.2 The Two-Level Encoding Scheme

Our preliminary results from the raw graphics protocol (see section III-B) indicated that the largest amount of bandwidth was consumed by pixmaps being sent as raw data for copying onto the display (e.g., little icons on applications or large images in image viewers). Since these consisted of individual pixel data rather than control information, the worst possible outcome of such data being corrupted would be some pixels being displayed in the wrong color. Experience with the InfoPad showed that, while such errors create a less pleasing display to the user, it is nonetheless acceptable [3], [4]. There was no reason to incur the large overhead of error correction just to protect the pixel data.

We decided to use the same, two-level encoding scheme that the InfoPad project used. We arranged the packing of information so that all the control information comes first and the pixel data (if any) comes last. The error correction system only corrects the first portion of the message which contains the control information. The number of bytes that are encoded is stored in the header of each request so that the other side knows how to re-assemble the message. Note that the unencoded data is never retransmitted unless the header could not be read (see section II-B.3).

B.3 Error Detection and Retransmission

Despite the large error correcting capacity of the Reed-Solomon code, measurements with our emulation environment showed that there were a large number of errors that the code could not correct [5]. The code would still detect a lot of these errors though. Furthermore, most of the requests had only small amounts of encoded control information (generally less than 100 bytes), but fonts were all encoded and resulted in particularly large requests (from 4Kbytes for the small fonts to 12Kbytes for the larger ones)[6]. In such cases there was a substantial probability that the request would suffer uncorrectable errors. In order to deal with such errors, an acknowledgment and retransmission scheme was developed.

The system operates as follows:

- Each request has associated with it a 16-bit ID. IDs are incremented for each request. After the X-server sends a request to the terminal it stops and waits for an acknowledgment.
- If the terminal cannot decode the header, then it has no idea how to re-assemble the message since it does not know what portion of it is encoded or its total size. It therefore flushes its input[7] and sends an acknowledgment to the X-server requesting a full retransmission (ACK_RETX_COMP).
- If the terminal decoded the header properly, it proceeds to read the rest of the message and to decode the encoded portion of

[5]In our noise model, this was generally independent of the actual noise rate and was due to lengthy burst errors.

[6]The actual font requests would be that big only when there was a cache miss and the full font structure had to be relayed to the terminal.

[7]Flushing the input means removing all data at the input queue that is still waiting there.

the message. If it cannot decode the encoded portion properly, it retains the unencoded portion and throws the encoded portion away[8]. It then sends to the X-server an acknowledgment requesting retransmission of only the encoded portion (ACK_RETX_PART).

- If the terminal managed to decode both the header and the encoded portion properly, it sends to the X-server an acknowledgment that asks it to proceed with the next request (ACK_OK) and then reassembles the message and dispatches to the appropriate drawing routine.
- If the X-server receives an ACK_RETX_COMP it retransmits the whole request and waits for another acknowledgment.
- If the X-server receives an ACK_RETX_PART it retransmits only the encoded portion and waits for another acknowledgment.
- If the X-server receives an ACK_OK it proceeds with the next request.

Note that the acknowledgment and retransmission scheme could increase the latency substantially if a request has to be retransmitted multiple times before it is received correctly. This did not seem to be a problem in practice. At the highest BER the system was designed for, we observed no request being retransmitted more than once in any of the sessions. Acknowledgments are carried on the same channel that carries all the other requests. The above procedure only describes the process for acknowledging requests sent from the X-server to the terminal. In the other direction things have been purposely kept a lot simpler. If the X-server receives any request it cannot properly decode, it simply ignores it and proceeds to the next one. The reason for this is that if one were to acknowledge requests in both directions, both directions would need timeouts in case the ACKs get corrupted. Using symmetric acknowledgments is particularly complex[8], while the consequences of asymmetric acknowledgments were not serious enough to justify the extra complexity. In fact, the reason why we did not use finer grain acknowledgments is that packet level acknowledgments require a symmetric acknowledgment scheme[9].

Again, despite the high error detection capacity of the Reed-Solomon code, it is still possible for some errors to remain undetected (see section III-C). Such errors will result in unpredictable behavior. It was, therefore, deemed necessary to provide an additional system of error detection. We decided to use a CRC that is widely used in modems (since the noise found on modem lines is very similar to the noise found on wireless channels). The CRC is based on the polynomial $x^{16} + x^{12} + x^5 + 1$. Before the encoded portion of the message is actually encoded, a CRC for it is calculated and inserted into the message header[10]. On the terminal side, when the message is decoded, the CRC is calculated again and compared to the value found in the header. If the two do not match, an ACK_RETX_PART is sent to the X-server[11].

[8]It is not considered a significant error if the unencoded portion is corrupt which is why we did not encode it in the first place.

[9]Another reason was that it would make the overhead higher by transmitting a lot more acknowledgments.

[10]Note that the CRC cannot be performed after the message is encoded. If it was, it would declare the data corrupt even after the Reed-Solomon code had corrected it (if correctable), and ask for an unnecessary retransmission.

[11]The requests going from the terminal to the X-server (including ACKs) are also encoded with both the CRC and Reed-Solomon codes. They are just not acknowledged in any way.

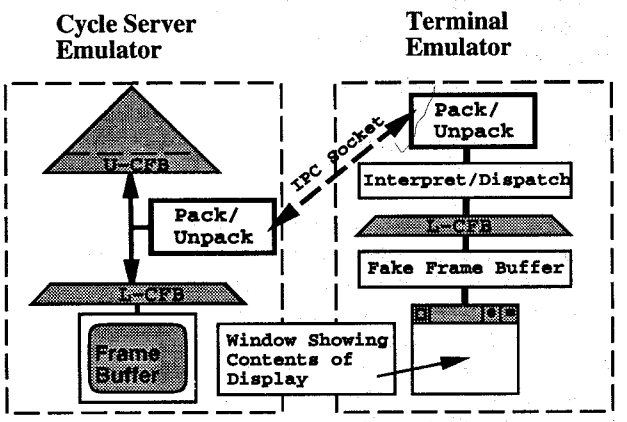

Fig. 4. The structure of the emulation environment.

III. Results and Measurements

A. The Emulation Environment

In order to test the raw graphics protocol (as well as the final protocol) and make some basic measurements on it, an emulation environment was built. This environment consists of:

- A workstation connected to a network to act as the cycle server. The workstation has to be X-compatible and capable of running the modified X-server.
- Another computer connected to the same network so that it can communicate with the first. This computer has to have an unmodified X-server running, in order to run the terminal emulation application.
- A modified version of the X-server that has been partitioned in accordance with the raw graphics protocol. This X-server has to be identical to the original X-server except for the fact that the information intercepted at the partition in accordance with the raw graphics protocol is sent via the network to the terminal emulation application running on the second computer[12].
- A terminal emulation application that runs on the second computer. This consists mainly of the software that will interpret the protocol on the final terminal hardware, except for the fact that it draws into an area of memory instead of a real frame buffer. It displays the contents of the fake frame buffer into an X window.

Figure 4 shows the final structure of the emulation environment. The cycle server emulator runs on a Sun 4/260 running Unix. The modified X-server actually displays the contents of the frame buffer on the original screen so that they can be compared with the output of the terminal emulator. It communicates with the terminal emulator using TCP/IP sockets (the main UNIX IPC substrate). The terminal emulator contains the code that interprets the protocol and draws to the fake frame buffer. It is actually an X-application itself (which is why it should not be allowed to connect back to the modified X-server). We ran our terminal emulator on a number of Sun platforms running UNIX.

The terminal emulator also contains code which dumps data about the requests to two files, allowing measurements to be made. The final version also includes noise injection code (to simulate a noisy wireless channel) and error correction, detection and retransmission code.

[12]Strictly speaking, this is not absolutely true. We had to modify the server to assume a resolution of 640 × 480 and recieve input from the terminal emulator instead of the keyboard and mouse.

Mosaic	Total Duration in Seconds	460
	Total Bytes Transferred	6706669
	Average Transfer Rate (bytes/sec)	14611
	Maximum Number of Bytes in 1 sec	101406
Frame	Total Duration in Seconds	950
	Total Bytes Transferred	6079939
	Average Transfer Rate (bytes/sec)	6406
	Maximum Number of Bytes in 1 sec	44875
Emacs	Total Duration in Seconds	649
	Total Bytes Transferred	812601
	Average Transfer Rate (bytes/sec)	1254
	Maximum Number of Bytes in 1 sec	31497

TABLE I
GLOBAL RESULTS FOR RAW GRAPHICS PROTOCOL

Mosaic	Total Duration in Seconds	998
	Total Bytes Transferred	4738738
	Average Transfer Rate (bytes/sec)	4752
	Maximum Number of Bytes in 1 sec	40216
	Total Reed-Solomon overhead (%)	17.98
Frame	Total Duration in Seconds	1462
	Total Bytes Transferred	5120239
	Average Transfer Rate (bytes/sec)	3504
	Maximum Number of Bytes in 1 sec	26110
	Total Reed-Solomon overhead (%)	23.55
Emacs	Total Duration in Seconds	862
	Total Bytes Transferred	1123082
	Average Transfer Rate (bytes/sec)	1304
	Maximum Number of Bytes in 1 sec	18795
	Total Reed-Solomon overhead (%)	45.74

TABLE II
GLOBAL ECC RESULTS FOR FULL GRAPHICS PROTOCOL

Our emulator environment allowed us to make several sets of measurements to evaluate the overall performance of the protocol. Based on these results, we modified some of our design decisions and set targets for the future development of both the protocol and the hardware for the terminal. These measurements also allowed us to evaluate the feasibility of the concept of higher level protocols.

Two sets of measurements were taken. The first set of measurements was taken before the inclusion of error correction, detection and retransmission (on the raw graphics protocol alone). The second set of measurements was taken on the overall final protocol and was used to evaluate the error correction and retransmission protocols.

The primary goal of the measurements made on the raw graphics protocol was to allow us to see which requests were being used most frequently so that we can optimize them further, and to give us some idea of what to expect for a bandwidth requirement. This depends on the type of application used, and in particular on the graphical content of the application. We used three applications: Mosaic World Wide Web Navigator (high graphics content), FrameMaker word processor (medium graphics content), and Emacs editor (low graphics content).

B. The Raw Graphics Protocol Measurements

Table I shows the global results of the first set of measurements.

From the table, the average bandwidth requirement is 15 Kbytes/sec or 120 Kbits/sec and the maximum bandwidth required for a one second period is 100 Kbytes/sec or 800 Kbits/sec.[13]

More detailed results are given in [4].

C. The Final Protocol Measurements

C.1 The Effect of the Error Correction Code

Table II shows the same information as Table I but is updated to reflect the results obtained for the full protocol. All of the measurements were taken with a burst mode noise source and a BER of 10^{-3}. The percentage of overhead due to the Reed-Solomon error correction code is indicated. This overhead is substantially below the theoretical 66% because most of the data is not encoded. As one moves to applications that have a lower graphics content, the percentage of traffic that is due to unencoded data decreases, and therefore, the effective overhead increases. The maximum overhead occurs during the Emacs session which has about 46% overhead.

[13]These values were calculated using the results from the Mosaic sessions at a BER of 10^{-3} since these displayed the worst case behavior.

C.2 The Effect of Retransmissions

Table III shows information relevant to the retransmission overheads. All measurements were taken with a burst-mode noise system at a BER of 10^{-3}. Similar measurements were made at lower BERs but the results are not included here. All measurements at lower BERs showed reduced retransmission overhead. The overhead due to timeout traffic is also listed. Both the timeout traffic and the retransmission traffic are relatively small even at a BER of 10^{-3} (which is the highest BER that the system was designed to handle). An interesting deviation in the results of the Emacs session arises because the user spent some amount of time reading pieces of text. During these times the X-server would remain idle and a large number of timeouts would occur. This explains the disproportionate percentage of timeout traffic for that session.

C.3 Overall Performance

The response rate in the final system with the error correction and retransmission code was not sufficient to make accurate bandwidth measurements. Using the results of sections III-B and III-C, we can extrapolate to estimate what the bandwidth would be if the response time was the same as that of the raw graphics protocol. We used the equation below to calculate the effective bandwidth :

$$B_{eff} = (B_{raw} \times (1 + ECC_{ohd})) \times (1 + T_{ohd} + R_{ohd})$$

where

B_{eff} is the effective bandwidth requirement

B_{raw} is the corresponding bandwidth requirement for the raw protocol

ECC_{ohd} is the overhead due to the Reed-Solomon code

T_{ohd} is the overhead due to timeout traffic [14]

R_{ohd} is the overhead due to retransmissions

Using the above equation, we found the average bandwidth requirement to be 17Kbytes/sec or 140Kbits/sec. Similarly, the maxi-

[14]Timeout traffic is the traffic caused by acknowledgments sent because the terminal did not receive any requests from the X server for a while. In this case, it sends the last acknowledgment again assuming that the first one was lost. Such acknowledgments are redundant a lot of the time and are considered to be overhead.

Mosaic	Total bytes transferred	4397493
	Total bytes due to timeouts	68250
	Timeout traffic %	1.55 %
	Total bytes due to retransmissions	108234
	Retransmission overhead (%)	2.52 %
	Total requests	10154
	Total retransmissions	24
	% of requests due to retransmissions	0.23 %
Frame	Total bytes transferred	4323324
	Total bytes due to timeouts	53910
	Timeout traffic %	1.25 %
	Total bytes due to retransmissions	17810
	Retransmission overhead (%)	0.41 %
	Total requests	15220
	Total retransmissions	32
	% of requests due to retransmissions	0.20 %
Emacs	Total bytes transferred	757052
	Total bytes due to timeouts	72720
	Timeout traffic %	9.61 %
	Total bytes due to retransmissions	13065
	Retransmission overhead (%)	1.76 %
	Total requests	4972
	Total retransmissions	11
	% of requests due to retransmissions	0.22 %

TABLE III
GLOBAL RETRANSMISSION RESULTS FOR FULL GRAPHICS PROTOCOL

mum bandwidth required to satisfy a one-second peak was calculated to be 970Kbits/sec.[15]

IV. ANALYSIS AND CONCLUSIONS

A. Evaluation of the Protocol

One of the most important characteristics of the protocol that has not been discussed so far is its flexibility. The protocol does not define standard formats for the requests – only the headers and the two-level encoding scheme. The format of each individual request is completely flexible as long as all control information that needs to be protected by ECC is placed before all other information that needs no protection. While this was not originally one of our design targets, we soon realized that it was a particularly useful way of working around the disparate structures of the drawing routines.

One of the most important design goals was to keep the required bandwidth low. The protocol was designed with a 1Mbit/sec radio link in mind operating over a very short range. Given that rate, the average bandwidth requirements are easily satisfied. The peak rates, however, approach the available bandwidth. This means that generally, the system will operate very much within its capabilities and the bandwidth of the radio link is not likely to be a bottleneck. On the other hand, it points to the fact that when large transfers occur, latencies caused by the time it takes to get the data through will be on the order of a second. These latencies will slow the response time of the system. Also, multiple retransmissions of the same request would increase the latency, but we never observed such retransmissions in practice at a BER of 10^{-3}. Unfortunately, our emulator environment did not allow us to make any real measurements of the latency involved.

[15]These values were calculated using the results from the Mosaic sessions at a BER of 10^{-3} since these displayed the worst case behavior.

The second goal was to maintain the low power properties described in section II-A.2. Generally, if any work could be performed on the cycle server without incurring a large bandwidth penalty, we opted to partition it out to the cycle server. There are some notable exceptions, but these are so rare under normal use that the overall overhead in computation would be small in comparison.

The final target was reliability in the presence of noise. Empirically, we observed a mean time to failure of of a few hours with a BER of 10^{-3}. Failure occurs when errors are undetected by the ECC and the CRC.

B. Limitations and Future Work

The protocol as described here, while complete and adequate by most counts, is by no means finished. There are a number of things that we would like to improve upon.

By far the most important is reliability. We consider the MTBF to be too low at a BER of 10^{-3}. In order to improve upon this we are considering the addition of a CRC for just the header, as well as replacing the 16-bit CRC by a 32 CRC, or 2 CRCs of 16 bits. Those two modifications alone would raise the MTBF to the order of years giving much more reliable operation.

Another improvement would be to extend the protocol to handle the painting of the cursor in a more intelligent way. This would cause most of the pixmap traffic in text-based applications to disappear, thus reducing bandwidth requirements. It would also cause some reduction in bandwidth requirements in high graphics content applications that make heavy use of the pointer input device (mouse or pen) and thus cause lots of cursor movement.

Also, during our measurement sessions we noticed that the protocol can cause traffic even when nothing gets drawn to the display. The main reason for this is elements (usually text) being "drawn" outside the clip region. While the display never gets changed for such a request, the routines that perform the normal drawing operations are still called so they create protocol traffic. We would like to change the individual requests involved so that this does not happen.

Finally, we would like to obtain some measurements of latency since these can be rather detrimental to the perceived performance of the system.

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