Development of a Sixteen Line Multiplexer

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DEVELOPMENT OF A SIXTEEN LINE MULTIPLEXER

BY

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B.S., Milwaukee School of Engineering, 1964

RESEARCH REPORT

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Orlando, Florida
ABSTRACT

This report explains the development of a telephone line multiplexer to be used with a computer based personal paging system. The large geographical area coverage made possible by computer processing results in many calls having to cross telephone tariff boundaries. Since system users cannot be expected to pay long distance charges, dedicated lines which cross tariff boundaries must be leased. Multiplexing applied to those leased lines reduces the cost of data transmission, and is, therefore, justified.

The design of the multiplexer proceeds from a specification set which is derived from user response requirements. Fundamentally, the response consists in advising the user, within a reasonable time, that a "page" has been accepted by the system.

The specification set is then partitioned into functional blocks which are modeled using flow charts and state diagrams. Logic design follows directly from the models.

Production of the multiplexer is followed by field installation. The savings resulting from the multiplexing are considerable.
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The intention of this chapter is to detail the problem of high telephone line cost associated with a time-shared computer system, and to show that a multiplexing technique applied to reduce the number of lines can reduce that cost. Specifically, factors of line costs, traffic analysis and multiplexing techniques are analyzed in order to derive a coherent set of multiplexer specifications. Chapter 2 and 3 describe, respectively, the system partitioning and the logic design techniques used.

Description of a Computer-Based Paging System

The system function is to make possible the contacting of an individual who cannot be located by telephone or other ordinary means. The information which initiates that contact is in the form of three or four decimal digits entered by means of the telephone Touch-Tone dial. The digits so entered are processed by a minicomputer controlled paging system which decodes the digits and initiates a coded call or "page" RF transmission. A miniature "page" receiver,
which is internally programmed for that code, responds by audibly alerting the individual who then takes some predetermined action, i.e., calls his office. A block diagram of the system is shown in Fig. 1.

![Paging System Block Diagram](image)

**Fig. 1. Paging System Block Diagram**

The mini-computer system is capable of handling over 100,000 paging receivers; thus it is suited to large areas such as metropolitan New York, Chicago or Los Angeles.

**Need for Multiplexing**

The need for a multiplexing device first became apparent in the Los Angeles area where eight Radio Common Carrier
(RCC) businesses lease time from a centrally located paging system. Because of local tariff regulations, each RCC was required to lease dedicated voice grade telephone lines between his tariff zone and the paging terminal. As an example, the cost of the leased lines for two of the eight RCC's (the closest and the furthest) is shown in Table 1.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Lease Rate/ Month/Line</th>
<th>Lease/Rate Year/Line</th>
<th>Lease/Year 16 Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1 miles</td>
<td>$40.16</td>
<td>$481.92</td>
<td>$7,710.72</td>
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<tr>
<td>56.2 miles</td>
<td>$160.81</td>
<td>$1,929.72</td>
<td>$30,875.52</td>
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Table 1. Typical Telephone Line Costs

The line costs shown in Table 1 represent the extended rate per mile as follows: $3.30 per mile up to 25 miles and $2.31 per mile from 26 to 100 miles. Fig. 2 illustrates the monthly lease cost for four, eight, twelve and fourteen lines up to 100 miles in length.

If a simple multiplexing process can be used to minimize the number of telephone lines, then the system cost can be reduced. The complexity, hence cost, of multiplexing is dependent on information rate and on the number of channels.

Fig. 2. Telephone Line Cost Versus Length
to be multiplexed. The number of channels multiplexed is determined by using a mathematical procedure known as traffic analysis, described below.

**Traffic Analysis**

Determination of the number of incoming trunk telephone lines required to handle a known quantity of users is fundamental to the specification of a telephone accessed terminal. Analysis is based upon the statistical nature of the arrival of telephone calls. The cumulative probability of a call being blocked (user getting a busy signal) is defined by the Poisson equation:

\[ p = e^{-\lambda} \sum_{m=0}^{\infty} \frac{\lambda^m}{m!} \]

Where \( n \) equals the number of trunks and \( \lambda \) equals traffic intensity in Erlangs or Traffic Units (T.U.). An Erlang or T.U. is "the average intensity in one or more traffic paths carrying an aggregate traffic of one call-hour in one hour (the busy hour unless otherwise specified)." 3. The probability of blocking defined by the Poisson equation is also known as the Grade-of-Service (GOS). Solutions of the Poisson equation (which relate Erlangs, the number of trunks

\[ 2H. \text{P. Westman, Reference Data for Radio Engineers,} \]

(Indianapolis: ITT Co. 1969) p. 31-16

\[ 3\text{Ibid. p. 31-9} \]
and Grade-of-Service) are included in the Appendix.

Thus, all that is needed to specify the number of trunks required for a given system is to determine the number of Erlangs and the desired GOS, then reference the tables. The number of Erlangs is determined from the formula:

\[
\text{Erlangs} = \frac{UXRxH}{3600}
\]

where \( U \) equals the number of users of the system, \( R \) equals the anticipated call rate at the busy hour and \( H \) equals the holding time for each call. Experience indicates that a holding time of twelve seconds, a call rate of 0.2 calls per hour per user and a GOS of between one and two percent are conservative and realistic numbers.

At the Los Angeles installation, each RCC has an initial capacity of 1200 users, so that the Erlang calculation becomes:

\[
\text{Erlangs} = \frac{1200 \times 0.2 \times 12}{3600} = 0.8
\]

A one to two percent GOS requirement then specifies a four trunk input facility, as listed in the table. In the fully expanded system, eg. 100,000 users, each RCC would have 10,000 users maximum which translates to the following traffic intensity:
Erlangs = \[ \frac{10,000 \times 0.2 \times 12}{3600} = 6.66 \]

Given that a one to two percent GOS is desired, reference to the table yields a trunk requirement of fourteen. Thus, the multiplexer must be able to handle from four to fourteen incoming trunk lines. Since existing data set hardware is available in blocks of four, expansion to sixteen input lines, with GOS improved to better than one percent, is desirable.

The preceding traffic analysis shows that a multiplexer must be able to combine at most, sixteen channels.

**Choice of a Multiplexing Technique**

Multiplexing is defined as the technique of carrying several channels over one telecommunication facility. Frequency division and time division multiplexing are the two basic methods of multiplexing. Frequency division multiplexing (FDM) involves apportioning the frequency spectrum of the facility equally between the channels to be multiplexed, assuming that each of the channels has the same bandwidth requirement. Thus, each channel, at the transmitting end, must be frequency shifted, filtered to remove out-of-band frequency components and transmitted. The reverse process

occurs at the receiving end, with discrete filters and demodulators required for each multiplexed channel. Complex and expensive filters and modems are required at both ends of the communications link for duplex communication.

An alternative to FDM is time division multiplexing (TDM), which functions by dividing the transmission time between the signals to be multiplexed. Ordinarily, two devices, which can be thought of as commutators, operate synchronously at both ends of the multiplexer link in order to sort one channel from another. The transmitting end commutator samples a particular channel for some finite time, and at the same time (allowing for propagation delay) the receiving end commutator samples the incoming data stream. The number of channels is limited by the requirement that each multiplexed channel must be sampled at a rate at least twice as fast as the highest frequency component required to be reconstructed from a multiplexed channel. 5.

A simplified form of TDM can be used when the data channels to be multiplexed contain quantized information (data which is made available in fixed size packets) and if the data...

packets are not required to be source specific. If the system requirements fall into the above category, a simple polling technique may be used, in which the channels to be multiplexed are sequentially sampled for activity (poled). If a channel is active, i.e., a data packet is ready for transmission, the polling device controls transmission of the data, waits for a response, if any, and subsequently continues to poll the existing channels.

Information entered into the previously described paging system can be quantized since the digits dialed can be stored and transmitted as a packet. Thus, the simplified TDM technique can be used to reduce the number of telephone lines required.

**Multiplexer System Specifications**

The preceding sections illustrate that multiplexing is a practical way to reduce the number of telephone lines required. In this section are listed the detailed specifications derived from the above study and from known characteristics of the paging system.

A. The number of users, hence, the number of telephone trunk lines to be multiplexed is from four to sixteen as specified in the traffic analysis. The
unit is to be easily field expandable in units of four lines.

B. Maximum time between entry of digits and confirming response from central system to be five seconds. This figure is consistent with a Telephone Company requirement that, once connected, a trunk must be used for at least six seconds in order to insure proper billing of the call. Although subject to verification by field experience, five seconds is judged to be a maximum time delay acceptable to any system user.

C. As derived from the existing paging system, the system responses to a user shall be as follows:

1. When a trunk line has been accessed, the multiplexer will generate a one second tone burst at 2025 Hz, thus alerting the user that the next digits entered will be interpreted as a "page".

2. After the digits entered have been multiplexed and transmitted to the central system, that central system will respond by issuing a valid indicator to the multiplexer if the digits entered were determined to correspond to an
active pager code. The valid indicator will, in turn, cause a valid message, consisting of an interrupted, two second, 2025 Hz tone burst to be returned to the user, indicating to him that the "page" data will be processed.

3. If the digits do not correspond to an active pager code, no response will be issued by the Central System, and an invalid message consisting of a two-second, 1012 Hz tone burst will be issued to the user by the multiplexer.

4. If a parity error is detected by the Central System, a request for re-transmission will be issued by the Central System.

5. Optional user responses, such as a voice recording in the case of an invalid message, will also be available.

6. After the valid or invalid message has been issued, the multiplexer will not accept further digits, except for Bulk User lines. A bulk user line is defined as being capable of entering more than one group of page digits during a single trunk access. Thus, after a valid or invalid message has been completed, another set of "page" digits may be entered
by the user without reaccessing the trunk line. A time limit of twenty seconds of use has been specified by the Los Angeles RCC customers.

D. Inherent in the telephone specifications is the necessity of a full duplex link between the Multiplexer and Central System. That is, digits are entered and transmitted from the multiplexer to the Central System and a response is issued in the reverse direction.

E. A straightforward design, easily maintained, was essential since many field servicemen are not familiar with digital logic systems.

Fig. 3 is a block diagram of the multiplexed paging system.

Fig. 3. Multiplexer System Block Diagram
Before proceeding with the design, certain system timing relationships must be specified as noted in the following section.

**System Timing Considerations**

A maximum user response time of five seconds divided by 16 channels equals 312.5 milliseconds as a maximum turnaround time from entry of the last digit to the beginning of the response message. Within this 312.5 millisecond window must occur the following:

A. Transfer of digit information from multiplexer to the computer system. A Larse Co. modem pair was chosen for data transfer. The transfer requires 113 milliseconds with the currently specified modem but can be decreased to 28 milliseconds by specifying a higher speed modem.

B. Computer interrupt and sub-routine processing. The software is designed to have no more than a 100 millisecond delay between an interrupt and the generation of a valid or request-for-repeat response.

C. A valid or request-for-repeat response from the CPU will cause a tone burst at 1200 Hz (valid) or
800 Hz (repeat of 50 millisecond duration to be transmitted to the multiplexer. A phase-locked-loop tone decoder detects the presence of either tone and initiates the proper action within the multiplexer. The absence of either tone is interrupted as an invalid number response.

Propagation delay due to the length of the telephone line is approximately $\sqrt{\varepsilon_r}$ nanoseconds per foot. The square root of the dielectric constant ($\sqrt{\varepsilon_r}$) for polyvinyl chloride (PVC) insulation, at the telephone frequencies, is roughly 2.0 and decreases to 1.5 if better insulators such as teflon are used. Therefore, the propagation delay for a 100 mile line insulated with PVC equals $2.0 \times 5,280 \times 10^2$ nanoseconds or 1.056 milliseconds. The propagation delay time may then be ignored for lines less than 100 miles in length. A timing diagram showing a complete multiplexer transaction with the computer is shown in Fig. 4 on the following page.

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Referring to Fig. 3 and Fig. 4, when a user enters the last digit of a series, the information is transmitted through the Data Set, the modulator and demodulator to the computer. The computer in the Central Unit then decodes the data and activates a tone generator which transmits information back to the multiplexer. The entire transaction can take, at most 312.5 milliseconds.

The preceding information has shown the need for multiplexing. By means of analysis of the system, a coherent set of device specifications has been generated. The following Chapter details the partitioning of the multiplexing device into sub-units.
Given the specification and timing considerations listed in Chapter I, design of the multiplexer could proceed directly. However, constraints imposed by specifying ease of serviceability and field expansion indicated that a thorough study of partitioning be undertaken. Optimum partitioning would result in minimum-time-to-repair (MTTR), minimum degradation of the multiplexer due to failure of one component part and minimum system "down time" when field expansion becomes necessary.

Since each incoming telephone line must be controlled asynchronously and independently and on that same line are entered a series of 3 or 4 digits which are temporarily stored, a functional partition called a "Supervisory and Register" (S & R) was defined. The S & R block satisfied the constraints in the form of a single printed circuit (PC) board in that a malfunction on one line could quickly be identified with that board and the board replaced by another without stopping the multiplexer or disturbing any other line. Field expansion was as simple as plugging additional S & R boards into a pre-wired back plane assembly.
The timing and control of the polling process was common to the entire system, thus a PC board handling that control was partitioned and called the "Scanner" board. The Scanner met the constraints listed in that failure of all lines indicates that it should be replaced and, since it is specified to poll all sixteen S & R's, field expansion requires no changes.

Digit code translation and parity generation are required for each channel but since only one channel transmits at a time, these functions can be shared. A block called Signal Conditioning was partitioned and met the constraints in the same manner as the Scanner board.

Modulation, serialization of the information and tone detection were partitioned into one block called the Remote Communications Board, since all those functions interface the outgoing telephone line. Demodulation and tone generation functions at the computer end of the multiplexer link were grouped on a single PC board called the Central Communications Board. The following paragraphs detail the functions of each partition.

The S & R Board interfaces with each Data Set (which contains the Touch-Tone frequency decoders) and performs the following functions:
1. Recognizes a ring signal on the incoming trunk.
2. Returns a ring acknowledge tone burst to the user.
3. Temporarily stores the digits entered.
4. Asserts a request signal when the correct number of digits have been entered.
5. Returns Valid or Invalid message to the user in response to the detected tone burst from the Central System.
6. Provides various time-outs so that a user may not access the terminal for an unnecessarily long time.

The Scanner Board exercises overall control of the multiplexer, interfaces with the S & R Boards and the Remote Communication Board, and functions as follows:

1. Sequentially polls the four to sixteen S & R Boards for activity in the form of a request.
2. Generates a Grant signal which puts data from the Requesting S & R Board on the data bus to the Signal Conditioning Board.
3. Maintains control of the Modem and the Tone Decoders.
4. Generates the "window" for detecting the valid or repeat response from the Central System.
5. Generates a signal which, after all S & R's have
been polled once, causes a bit stream of sixteen logic ones to be sent to the Central System. The all ones word is interpreted by the software as an activity check in the absence of any other inputs to the system.

The Signal Conditioning board interfaces with the data bus from the S & R boards and with the data bus to the Remote Communication board to perform the following function:

Conversion of the Binary Coded Matrix (BCM) representation of the digits entered (as produced by the Data Sets) to a Binary Coded Decimal representation. That conversion is necessary for two reasons: one, that at some future time an end-to-end or dial pulse Data Set (which produces BCD directly) may be used in the system and two, that a conversion from sixteen to fifteen bits is required for parity bit inclusion in the serial bit stream, since the modems used accept only sixteen bit parallel words for transmission. Compression of the data from 16 to 15 bits is made possible by eliminating the unused bit combinations from B16 to F16 in the hexadecimal representation of the telephone binary coded decimal numbers. The method of compression consists of multiplying one BCD number by 10 and adding
the next BCD number to it. Since two BCD numbers (telephone digits) can represent at most 100 combinations, only seven binary bits \((2^7 = 128)\) are required when the multiply and add algorithm is applied. The Signal Conditioning board also generates the odd parity bit for inclusion in the bit stream.

The Remote Communications board interfaces with the Signal Conditioning board, the Scanner board and the telephone line to the computer system and provides the following functions:

1. Conversion of the parallel 16 bit word from the Signal Conditioning board to a serial FSK signal to the computer system.

2. Detection of the response tones from the computer system.

The Central Communications board interfaces with the telephone line from the Multiplexer and with the Digital Equipment Co. DRIIC, a digital I/O port for the PDP 11 computer. Its functions are the inverse of the Remote Communications board.

Summarizing the partition, a block diagram showing the interconnection between printed circuit cards A, B, C and D above is shown in Fig. 5.
Fig. 5 Multiplexer Block Diagram
The partitioning completed above, while adhering to the constraints listed at the beginning of the chapter, also forms the basis for proceeding with logic design, since functional blocks are now identified with a physical location. The next chapter illustrates the actual logic design procedures used to implement the functions required.
CHAPTER III

LOGIC DESIGN PROCEDURES

This chapter briefly describes the logic implementation of the functions defined and partitioned in the previous chapters. The Transistor-Transistor logic (TTL) family was chosen because replacement devices were already available at the field sites, field personnel were familiar with the family and complex functions such as coders were readily obtainable. TTL has an adequate dc noise margin (400 millivolts) for the expected environment. Design aids used included the sequence diagram, the state diagram and a common combinatorial minimization technique, the Karnough Map.

S & R Design

The S & R board was first characterized using a sequence or flow chart; see Fig. 6. Logic implementation proceeded directly from the flow chart. That first logic diagram


Fig. 6 Supervisor and Register Flow Chart

B.S. = Bi-Stable
M.S. = Mono-Stable
consisted primarily of monostable multivibrators and flip-flops, with some gating required for clearing functions and flip-flop steering. Note that Fig. 6 contains a code describing the storage element required. Values for the timing components of the monostable elements were calculated according to the manufacturers' data sheets. After some minimization, the logic diagram was completed and the artwork generated. The design did not pass through a breadboard stage due to the straightforwardness of design and an intensive "desk check". While the PC board was being fabricated, a test set was designed and built so that isolated testing of the finished board could be done.

Scanner Design

The Scanner board was modeled using a State Diagram shown as Fig. 7. A ring counter rather than a Johnson or binary counter was chosen to implement the state diagram because of the requirement for ease of maintainability. While the ring counter does have the disadvantage of using more bi-stables than other counter types, generation of the bi-stable steering equations is simple and easier to troubleshoot. A problem inherent to a ring counter, that of assuming more than one state, is reduced by sensing that condition and causing a reset to occur. The same logic, excepting one
Start

No Request and Address
15 Current

No Request

Clock Pulse

Clock Pulse

Valid Received

Address 15
Not Current

Valid Removed

Clock Pulse

Address 15 Current

State Definitions:
1. Increment Counter
2. Test for Request
3. Set Grant and disable tone detector
4. Start Valid and Repeat timeout
5. Valid command generated
6. Invalid command generated
7. Set double repeat inhibit
8. Remove Grant
9. Transmit all one's

Fig. 7 Scanner State Diagram
gate, is used to detect the absence of any state, which also causes a reset to occur. A synchronous, rather than a ripple design, is used to increase noise immunity on the signal lines coming from the interface and to provide for settling or de-skewing times without adding more mono-stables. The design was not breadboarded due to straight-forward design and intensive "desk check". As with the S & R board, a test fixture was designed and built during the time of fabrication of the board.

**Signal Conditioning Design**

The Signal Conditioning board consists only of combinatorial logic and, as mentioned above, converts the BCM code to BCD as well as performing a multiplication and addition function. Since BCM is a non-weighted code, three of the four digits presented in parallel are converted first from the BCM to Unary, using the Motorola MC4038P logic pack. The Unary coded signals are then re-coded in BCD by the use of Texas Instruments' SN74147N logic pack. The only unary signal not handled by the BCD encoder is decimal 10 (zero by telephone usage convention), and that BCD is generated using discrete gates following the BCD encoder. The bit reduction scheme required in order to include parity checking was implemented using a Read-Only memory (which stored the quantities 10, 20, etc. to 100) addressed by the BCM digit
code. The output of the ROM, seven bits wide and standard binary weight, is arithmetically added to the binary representation of the next digit, resulting in a seven bit binary weighted quantity.

Remote Communications Design

The functions of the Remote Communication Board were implemented using a commercially available send only modem (Larse Company) and phase locked loop tone detectors tuned to the Valid, Repeat and Reverse frequencies, i.e.; 800, 1200 and 2200 Hz. A tone detector disable mono-stable is included in order to eliminate the effects of saturation of the tone decoders immediately following a transmission from the modem. Additional noise immunity is obtained by adding a 390 microsecond delay following each tone decoder. An amplifier is required to increase the signal amplitude to the tone decoder, since the signal amplitude may be as low as -25dbm. Diode clamping is used to insure non-saturation of the operational amplifier.

Central Communications Design

The functions of the Central Communications Board are implemented using a receive-only modem, three commercially available tone oscillators, an amplifier following the oscillators, and logic to enable the proper oscillator and
to generate a CPU interrupt when a new word was received.

**Supportive Hardware**

The multiplexer requires a five and a twelve volt power supply, a mounting rack, a complement of Data Sets interfacing the incoming telephone trunks directly and a Touch-Tone test set permitting local testing of the multiplexer. These items were either commercially available or were not designed as a part of the project and will not be detailed further.

Work described in this chapter resulted in obtaining PC boards which are optimally partitioned as to function. The PC cards were assembled and interconnected by means of a wired back-plane using wire wrap techniques. A very few (approximately ten) changes to the PC boards were required in order to make the system function to the specifications stated in Chapter I.
CHAPTER IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The preceding chapters illustrate how the multiplexer was specified and designed. Production quantities of the multiplexer were assembled and are now in continuous use in the Los Angeles area. No field modifications were required in order to satisfy customer requirements. Thus, the objective of the project was attained and multiplexing has been shown to be an effective method of reducing the number of telephone lines required for a "paging" system. The economic savings resulting from multiplexing are significant. Refer to Fig. 8 and note the difference in cost between multiples of individual lines and a multiplexer handling the same quantity of data. The dotted lines represent multiplexer cost, and solid lines represent telephone line costs without multiplexing. The breakeven points for 4, 8, 12 and 14 lines are indicated, that is the distance at which multiplexing becomes less expensive than non-multiplexed telephone lines. Value analysis would result in reduction of the distance, thus opening more applications for the multiplexer.
Notes: 1. Solid lines represent non-multiplexed cost.
2. Dashed lines represent multiplexed cost.
3. Black circles show break-even points.

Fig. 8 Multiplexed Versus Non-Multiplexed Costs
Although the multiplexer device described in this report is a solution to the problem of high telephone line costs, cost reduction would increase its application range. Thus, a value analysis effort is recommended in order to reduce cost. Areas of potential cost reduction that became apparent during the design effort were the power supply system, the invalid message recorder and the modems.
APPENDIX

The following table is a selection from a published trunk loading capacity table, and represents solutions of the Poisson equation. 10

<table>
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<tr>
<th>Trunks</th>
<th>Erlangs for 0.1% GOS</th>
<th>Erlangs for 1.0% GOS</th>
<th>Erlangs for 2% GOS</th>
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10 H. P. Westman, op. cit., p. 31-14.
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