CALCULATION OF THE TRAFFIC CAPACITY OF A PRIVATE DATA NETWORK

M. E. Fakhr El Din and L. Peiram
L M Ericsson
Stockholm, Sweden

ABSTRACT

A private data network is considered. A stochastic model which accounts for the random nature of message generation is set up. The network in the calculation model is viewed as a queueing system consisting of a number of devices. By approximate methods the distribution of the response time, excluding processing, is obtained. The comparisons between the analytical and simulation results show good agreement for the cases with low traffic when the model is not strongly affected by the independence assumptions.

1. INTRODUCTION

A main characteristic of an inquiry/response data communication system is the response time, which is defined as the time interval between the operator pressing the sending key of a terminal in the system and the arrival of the first character of the response at the terminal buffer. This response time consists mainly of the time spent by a message in transmission on the channels between the terminal and the central computer, waiting for free buffers in the concentrators and processing in the central computer.

In this paper the attention is focused on the contribution to the response time which is due to the transmission and waiting on the routes between a terminal and central line concentrator (CLC) only. As a part of future work the processing time will be considered.

2. NETWORK DESCRIPTION

The network is shown in fig. 1 and its function is shortly described here.

Fig. 1 Network configuration

The offices are connected to the regional line concentrators (RLC) via a local line which can be shared by a number of offices. An office may include more than one terminal. The terminals in one office are connected to a common control unit.

One RLC can connect up to 16 local lines and has 2 buffers of 125 characters per local line for the messages to and from the terminals.

The transmission between the offices on a local line and the RLC is controlled from the RLC by a polling-selecting procedure. The offices are polled in cyclic fashion for messages to the central computer and are selected for messages from the central computer.

The central lines are connected to the communication computer via a hardware unit called the central line concentrator (CLC). CLC is used to carry out transmission checks, gives the status for lines and transmits and receives messages from the communication computer. One CLC has the ca-
capacity to be connected to max. 16 regional line concentrators RLC via four-wire central lines which are used for full duplex transmission.

The complete network is connected to the central computer via a communication computer. The communication computer, which is a general purpose computer, takes the main load off the central computer and controls the data flow and supervises the network.

2.1 Polling procedure

The RLC starts the polling procedure by sending down the local line to each office's polling request message to an office. The control unit of the office in question receives the polling message and allows one of the office terminals to send a data block (positive polling), fig. 2a, or EOT "End of transmission" which means that there is no data block to be sent to RLC (negative polling), fig. 2b. If a data block is received by RLC, then it carries out a transmission check and answers with an unaddressed "ACK" or "NAK" back to the office. The procedure is repeated for the next office on the local line in question and so on. The polling procedures on different local lines connected to the same RLC are completely independent.

2.2 Selecting procedure

If RLC has received a message from the communication computer via CLC the polling procedure on the appropriate local line is stopped upon receiving an "EOT", "ACK" or "NAK" from the office which is under polling. Afterwards RLC sends a selecting message containing the address of the appropriate office to all offices on the local line in question. The control unit of the addressed office answers this selecting message and the message is then transmitted to the terminal, fig. 2c. After completion of this transmission the polling procedure is continued, where it was interrupted. Note that two messages towards the offices (terminals) are always separated by polling of an office.

Fig. 2a Transmission with Positive Polling.

Fig. 2b Transmission with Negative Polling.

Fig. 2c Transmission with Selecting.

3. THE MODEL

A stochastic model, where the network is viewed as a queuing system consisting of a number of devices, is set up. Each device represents a facility in the network. An arrival (or generation) pattern for the messages, a service (or occupancy) pattern for the devices and a service discipline for the transmission of the messages through the network are assumed in the model.

3.1 The devices

The devices in the model are:

1. The office common buffer in the control unit.
2. The local channel used for half-duplex transmission.
3. The incoming RLC buffers where messages from the office common buffer (input messages) are stored.
4. The outgoing RLC buffers where messages to the office common buffer (output messages) are stored.
5. The central channel used for transmission from RLC to CLC.
6. The central channel used for transmission from CLC to RLC.
7. The incoming CLC buffers where messages from RLC are stored.
8. The outgoing CLC buffers where messages to RLC are stored.

3.2 The message generation pattern

The message generation pattern is assumed to be stochastic in space and time. More precisely, the messages are assumed to be originated at time points according to a Poisson process. The message type (number of characters) generation follows a probability distribution \( P \). In this context a message is considered to be composed of two parts, namely the inquiry and the response. The inquiry corresponds to the information sent from the terminal to the central computer (input message) and the response to the inquiry sent back after processing from the central computer to the terminal (output message).

If such a message consists of \( x \) characters for the inquiry and \( y \) characters for the corresponding response, then generally the distribution of \( x \) and \( y \) is a two-dimensional distribution

\[
f(x,y) = P(x,y)
\]

In the model \( x \) and \( y \) are assumed to be independent. Then it follows that

\[
f(x,y) = f_1(x) \cdot f_2(y)
\]

where \( f_1 \) and \( f_2 \) are the marginal probability functions of \( x \) and \( y \) respectively.

The input messages are assumed to be generated at different terminals independently. The "call" intensities may be different for different terminals.

Due to the additive property of independent Poisson processes the terminal messages from terminals in the same local office add up to a Poisson process of messages at the office common buffer. The "call" intensity of this process is simply the sum of the intensities of the terminals. Similarly we may consider the total "call" intensity for the offices on a local line.

3.3 The occupancy pattern

The devices under consideration will be occupied due to transmission and/or waiting for subsequent buffers to become free. The total time for a message (inquiry and response) with a specified number of characters through the network is composed of the following parts (see fig. 3).

The terminal operator presses the sending key (request to send).

Waiting for the local office outgoing buffer to become free = external delay = \( t_1 \).
Waiting for the RLC to poll the office = polling waiting time = \( t_2 \).
Transmission over the local channel to RLC = \( t_3 \).
Waiting in incoming RLC buffer for the incoming CLC buffer to become free = $v_1$.

Transmission over central channel to CLC = $t_0$.

Waiting for processing + Processing + Processor queuing + Transmission to CLC = $t_c$. 

Waiting for free outgoing RLC buffer = $v_2$.

Transmission over central channel to RLC = $t_3$.

Waiting in outgoing RLC buffer for the beginning of selecting = $v_4$. 

Transmission over local channel to the terminal = $t_4$.

**Fig. 3 Time chart for an inquiry/response message.**

The response time $t_r$ for an inquiry/response message is thus

$$t_r = t_w + t_p + t_c + t_f + t_e$$

where

- $t_w$ = the internal delay
- $t_p$ = the polling waiting time
- $t_c$ = time in central unit, including waiting for processing, queuing and transmission to CLC
- $t_f$ = transmission time for one character (RLC→terminal)
- $t_e$ = transmission time of polling request message

In this paper the contribution $t_c$ to the response time $t_r$ is considered where,

$$T = t_4 - t_c$$

**3.4 The service discipline**

The service discipline is partly given by the polling-selecting procedure and by the fact that an inquiry (response) has to wait in a buffer until the buffer of the following device is free. Queues build up only in front of the local office buffer as are served in a FIFO (first in first out) basis.

4. THE CALCULATION METHOD

The response time is the sum of the holding times (service time) at each device a certain message (inquiry + response) experiences in tying up the network. An exact treatment of its distribution is rather complicated. The method used is an approximate one which has been developed for complex common control systems by Björkland and Elldin [1] and applied to marker systems by Szybicki [4] and others. The method uses a weighting between the constant holding time and the exponential holding time cases to obtain the distribution for the sum is deduced. This assumption yields a reasonable approximation at least for cases when the traffic is low. The parameters required for the calculation method and for each device are

a) Mean holding (service) time
b) Number of sources
c) Availability
and for the whole network
d) Call intensity

An account follows of the calculation methods for the means and the variances of the components of the response time.

4.1 The polling waiting time $t_p$

The polling waiting time is the time an inquiry (input message) occupies a local office common buffer until the office is polled from the corresponding RLC. RLC polls the local offices on a certain local line in cyclic fashion, eventually with interruptions for the transmission of responses (output messages). This waiting time will depend mainly on the period of the polling cycle, $T$, that is the time needed for the RLC to poll all offices, say N on a local line. Moreover $T$ depends on the office position in the cycle at an arbitrary time point. Thus the polling cycle time, $T$, is composed of the time for transmission of $N$ polling request messages, $U$ inquires (input messages) and $M$ responses (output messages) during the cycle. Here, $U$ and $M$ are random variables with means $E(U)$, $E(M)$ and variances $D(U)$, $D(M)$.

The polling request message is answered by either STX in the case of positive polling (fig. 2a) or by EOT in the case of negative polling (fig. 2b).

Thus, the period of the polling cycle is given by

$$T = N \cdot t_0 + \sum_{i=1}^{U} t(x_i) + \sum_{j=1}^{M} t(y_j)$$

where

- $t_0$ = time for transmission of polling request message and either STX or EOT
- $x_i$ = total number of characters in the case of positive polling including the length of an inquiry (input message)
- $y_j$ = total number of characters in the case of selecting (fig. 2c) including the characters used for addressing the terminal and the length of a response (output message)

and $t(x) = x + \gamma = time to transmit x characters (see sect. 4,3)

In this formula the way in which the $x_i$ and $y_j$ correspond to the messages in the sense of section 3.2 is not explicit. In fact the inquiry ($x$) and the response ($y$) of a message may belong to different polling cycles. This leads to the conclusion that the sequence of polling cycle times $T_1, T_2, \ldots$ generally is not a sequence of independent variables. Moreover it is not always possible to treat the $x_i$ and $y_j$ as independent variables in the above formula.

However, according to the assumption of independence between the lengths of the inquiry and the response given in 3.2 the $x$'s and $y$'s in the formula for $T$ (above) may be treated as independent random variables. Moreover the sequence of successive cycle times $T_1, T_2, \ldots$ will become a sequence of independent identically distributed random variables. Accordingly the instants of return to a certain local office form a renewal process.

From general renewal theory we then get the following expression for the mean polling waiting time.

$$E(t_p) = \frac{1}{2} \cdot E(T) \cdot (1 + C^2(T))$$

where $E(T)$ = mean value of $T$

$C(T) = D(T)/E(T)$ (coefficient of variation of $T$)

We have

$$E(T) = N \cdot t_0 + E(U) \cdot E(t(x)) + E(M) \cdot E(t(y))$$

To get an approximation for $C(T)$ we assume that $U$ and $M$ are independent of the types of messages generated and of each other. Then for the variance of $T$, $D(T)$, we have,

$$D^2(T) = E(U) \cdot D^2(t(x)) + D(U) \cdot E^2(t(x)) + E(M) \cdot D^2(t(y)) + D(M) \cdot E^2(t(y))$$

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Here \( t \) and \( t(x) \) are independent random variables, since \( t \)

According to the assumptions in sect. 3, the arrivals at the local office buffer form a Poisson process. When an input message occupies the local office buffer, then this buffer will not be free until the local office has been polled by the RLC and the inquiry is transmitted. Thus the "service time" in the local buffer is

\[
E(t(x)) = \frac{E(x)}{c} + v
\]

The transmission time \( t(x) \) is more complicated. In fact the assumptions concerning the processing in the central computer must be considered. However, to yield a first approximation we put

\[
\mu \sim \mathcal{P}(\lambda)
\]

which would be the case if \( \lambda, \mu \) follow the Poisson law.

Let the line speed be \( c \) characters/sec and the total turnaround time be \( v \) sec. Then the time to transmit \( x \) characters on this line will be

\[
t(x) = \frac{x}{c} + v
\]

If \( x \) is a random variable with mean \( E(x) \) and variance \( \sigma^2(x) \), then

\[
E(t(x)) = \frac{E(x)}{c} + v
\]

5. THE SIMULATION

A clock-type simulation program written in FORTRAN was developed to serve as a model of the network in question. The results are presented in the form of the distribution of the time needed for the message through the part of network concerned and the average delay a message may experience. These results are used to examine the accuracy of those obtained with the analytical model. The outline of the program structure is shown in the block diagram, fig. 4.

The following parameters are determined and supplied to the program for a particular test:

- Number of offices or terminals in the network.
- Number of local lines.
- Number of central lines.
- Total input and output message intensity per office.
- The distribution of the message length.
- Lines speeds (character/unit time).
- Turnaround time on lines.

The network in the program is viewed as a number of blocks. Each block corresponds to a facility in the network, for example a local line. In the simulation the program runs between different blocks and executes different activities in time sequence. In front of each block the message is described by 4 elements. The values of these elements are used for determining the following: the time for an event, the arrival time of the input messages, the input/output message length, and assigning an office or a terminal for the input message. These values are used in the estimation within the block and are stored at the output of the block as queues. In the case of a busy facility the time of an event is marked only when the facility becomes free. If a facility is free, the transmission time and service time are marked as the event time.

The message is then moved to the next block in the program and the next event is then ordered.

In the case of a call (see block diagram) a new message is randomly chosen and put in the queue before the one considered is treated. Therefore there are always at least two messages in the program.
Fig. 4 Block diagram for the simulation.
6. THE ANALYTICAL AND SIMULATION RESULTS

The results of the analytical model and simulation are presented in this section. The examples studied concern the type of network shown in Table 1. The results are in the form of the distribution of the total delay a message may experience in the part of the network in question. (Table 2). The distribution for polling waiting time is also yielded by the simulation and is shown in (Table 3).

The analytical model gives an estimation of the loading for each facility and is given in (Table 4).

Table 1. The Studied Examples

<table>
<thead>
<tr>
<th>Network</th>
<th>A</th>
<th>B₁</th>
<th>B₂</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of offices per local line</td>
<td>8</td>
<td>9</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Distribution of terminals per office</td>
<td>1,1,2,2,2,3,3,3</td>
<td>1,1,1,2,2,2,3,3,3</td>
<td>1,1,1,1,2</td>
<td></td>
</tr>
<tr>
<td>Total number of terminals on a local line</td>
<td>17</td>
<td>18</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Number of local lines per RLC</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Total number of RLC</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Line speed character/sec</td>
<td>local line 150</td>
<td>300</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Line speed character/sec</td>
<td>central line 300</td>
<td>600</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Line turnaround time in milliseconds</td>
<td>40</td>
<td>20</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Message distribution</td>
<td>Input message</td>
<td>Probability</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>length (characters)</td>
<td>40</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Output message</td>
<td>Probability</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>length (characters)</td>
<td>40</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Call intensity per terminal message/hour</td>
<td>95</td>
<td>80</td>
<td>105</td>
</tr>
</tbody>
</table>

It can be seen that the distribution yielded by the calculations and simulations in table 2 agree fairly well for network A. The calculated values are lower than the simulated ones for lower values of t. For higher values of t the situation is reversed. The calculated mean agrees well with the simulated one. For network B the calculations and simulations were performed for two call intensities 80 and 105 messages per hour. The deviation between simulation and calculation values is more significant in network B₁ than in B₂, especially for higher values of t. This deviation may be due to the difference in loading on network facilities (table 4) between B₁ with lower loading and B₂ with higher loading (see Conclusions). However, the mean delay values agree rather well in both cases. The calculated and simulated total delay distribution as well as the mean agree well for the network C.
Table 2. The Complementary Probability Distribution of \( P(\tau > t) \)

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<td>tms</td>
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<tr>
<td>0</td>
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<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
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<tr>
<td>500</td>
<td>0.908</td>
<td>0.983</td>
<td>0.893</td>
<td>0.977</td>
<td>0.990</td>
<td>0.990</td>
<td>0.950</td>
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<tr>
<td>1000</td>
<td>0.121</td>
<td>0.326</td>
<td>0.187</td>
<td>0.251</td>
<td>0.690</td>
<td>0.595</td>
<td>0.191</td>
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<td>1500</td>
<td>0.724</td>
<td>0.283</td>
<td>0.404</td>
<td>0.573</td>
<td>0.800</td>
<td>0.673</td>
<td>0.400</td>
</tr>
<tr>
<td>2000</td>
<td>0.472</td>
<td>0.094</td>
<td>0.187</td>
<td>0.917</td>
<td>0.895</td>
<td>0.895</td>
<td>0.734</td>
</tr>
<tr>
<td>2500</td>
<td>0.380</td>
<td>0.016</td>
<td>0.083</td>
<td>0.819</td>
<td>0.850</td>
<td>0.850</td>
<td>0.734</td>
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<tr>
<td>3000</td>
<td>0.274</td>
<td>0.008</td>
<td>0.018</td>
<td>0.340</td>
<td>0.850</td>
<td>0.850</td>
<td>0.734</td>
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<tr>
<td>3500</td>
<td>0.195</td>
<td>0.006</td>
<td>0.018</td>
<td>0.040</td>
<td>0.850</td>
<td>0.850</td>
<td>0.734</td>
</tr>
<tr>
<td>4000</td>
<td>0.142</td>
<td>0.003</td>
<td>0.024</td>
<td>0.010</td>
<td>0.850</td>
<td>0.850</td>
<td>0.734</td>
</tr>
<tr>
<td>5000</td>
<td>0.082</td>
<td>0.004</td>
<td>0.015</td>
<td>0.001</td>
<td>0.850</td>
<td>0.850</td>
<td>0.734</td>
</tr>
</tbody>
</table>

Mean in secs. 2.710 2.458 1.320 1.601 2.928 2.878 1.580 1.609

\( \tau \) is given in section 3.3

Table 3 shows the distribution of polling waiting time \( t_p \) yielded by the simulations.

Table 3: Probability of Polling Waiting time, \( t_p \), exceeding \( t \).

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<tr>
<td>500</td>
<td>0.017</td>
<td>0.040</td>
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<td>1000</td>
<td>0.001</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Mean value in secs. 1.214 0.565 0.696 0.929

Table 4 shows the average load per device. For the device numbering we refer to section 3.1. It can be seen from the table that there are significant loading deviations for different devices in the same network. The highest loaded device is not the same for different networks. For networks B1 and B2 it can be seen that an increase in call intensity changes the situation concerning the highest loaded device. The reason for the low loadings in network C is the low call intensity and the high line speed for the central line.

Table 4: Average Load per Device in erl.(Analytical)

<table>
<thead>
<tr>
<th>Network</th>
<th>Device</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.026</td>
<td>0.324</td>
<td>0.890</td>
<td>0.592</td>
<td>0.469</td>
<td>0.659</td>
<td>0.207</td>
<td>0.373</td>
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<td>B1</td>
<td>0.013</td>
<td>0.060</td>
<td>0.289</td>
<td>0.072</td>
<td>0.532</td>
<td>0.625</td>
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7. CONCLUSIONS

It follows from the comparisons that, for high loading on the network facilities, the analytical method yields higher calculated values for the average time, \( \tau \), a message needs to tie up the part of the network studied than the simulations. For low loading the simulation yields higher values than the calculated values.

The analytical model is weakened partly by the approximations assumed in the calculations in section 4. The calculation method discussed may be used for practical purposes especially in cases when the need for high accuracy of the results is of secondary importance in the dimensioning of the network. The method is justified by the fact that the analytical model is less sensitive than the simulations as regards the size and complexity of the network. The computer time required for the simulation depends directly on the type of the network and its complexity.

The examples studied in this paper are all symmetrical, i.e. the total number of terminals on local lines are the same for all local lines. The effect of the network parameters on the total delay can be examined by studying another type of network which is not symmetrical. Moreover, it is clear that an increase in total number of terminals in the network, or in call intensity or in turnaround time, results in an increase of the total delay, whereas an increase in line speeds results in a decrease of the total delay.

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