CATV two-way systems: Variation of the total interrogation time.

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1975
CATV TWO-WAY SYSTEMS:
VARIATION OF THE TOTAL INTERROGATION TIME

by

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A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in
Electrical Engineering

Bethlehem, Pennsylvania
This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

DEC 9, 1975

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Acknowledgement

A word of gratitude to my thesis advisor, Professor Arthur I. Larky, and to Professor Bruce Fritchman. Their guidance and suggestions are most appreciated.

Further, the author wishes to acknowledge the cooperation of Mr. Danny Tang of Twin County Cable TV Co., which provided the system and equipment for analysis and measurement.
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ABSTRACT

The transmission of TV signals by coaxial cable was initiated a number of years ago to provide better reception in places particularly isolated from the off-the-air signal. The large number of CATV systems installed and the development of the techniques to provide two-way transmission without interference, brings about the possibility of an ordered audio-video and digital interaction between the subscriber's terminals of the CATV system, all under the control of a central computer at the head-end terminal.

The control information, in digital form, is sent to each terminal (Question Data Word), and each terminal sends back its status information (Answer Data Word) after executing any control actions required. Choosing the method of interrogation depends on the particular of each system; usually the task consists of applying the fastest method at the lowest cost possible.

Without attempting to exhaust the possibilities, six methods of interrogation are presented, comparing the total time necessary for interrogating all the subscribers of the system and receiving all the
corresponding answers, for different system parameters. Basically, the methods fall into two different procedures: in the first procedure the terminals are considered individually; (Methods I, II and III); while in the second, the terminals are arranged into blocks having a common delay range (Methods IV, V and VI).

The distribution of terminals in the system is expressed by taking their delay-distance from the head-end, independent of their physical location. Also, a redundancy in the interrogation process is assumed to provide a means for increasing the reliability of reception of QDW.

**Method I** - Each QDW is sent right after the ADW corresponding to the previous QDW is received.

**Method II** - The QDW are sent one after the other with a minimum possible pause between them. To avoid overlapping of ADW's it is assumed that the terminals have been sorted by delay and the interrogation follows that order.

**Method III** - Consists of sending the repetitious to a terminal; then waiting for the answers before sending the next repetitious to the next terminal.

**Method IV** - The M equal delay-width blocks are sorted by delay such that no terminal in block is interrogated before any member
of block $m$, but the terminals belonging to each block can be interrogated in any order.

**Method V** - All the terminals within a block are interrogated and all the corresponding ADW's are received before interrogating any other block.

**Method VI** - Arbitrary order of interrogation of blocks with arbitrary order of interrogation of the terminals within each block.

Determining the total interrogation time ($T$) for each method and comparing, it is found that although Method II is the fastest method, it is not always the best choice to increase speed and it is displaced by Method III, which in some cases provides the same interrogation speed at lower cost. Furthermore, under some conditions, the gain in interrogation speed for Method II is so small that, being the most expensive method, it is doubtful that it is worth using. Furthermore, the interrogation speed of the blocking-procedure methods are lower, but very close to Method II, thus they are a better choice in most cases, as they are less expensive to implement. A table showing the speed-method comparisons under the various conditions is given.
1. **Introduction**

When the TV receivers are located in mountainous areas or surrounded by high buildings, the off-the-air signal reception usually is extremely poor. Community Antenna Television systems were conceived and introduced about 25 years ago to solve this problem by means of a good antenna, located where the signal reception was better (i.e. top of a mountain or building) feeding the signal to the receivers by coaxial cable. Since that time, CATV has grown explosively, particularly during the past few years\(^{(1)}\). Currently there are about 2,500 cable systems in the U.S., serving more than 12% of those homes having TV receivers.

The user of such a system pays for a better signal in his receiver, but the programming is the same as on standard broadcast. Since the competition for bandwidth in the cable is less than by air, there are a number of channels available, bringing about the second stage of CATV. Special programming not available on standard broadcast is sold to the user by transmitting it using any of the free channels. Programs run continuously and monthly payment is at a fixed rate that is independent
of the number of programs viewed. Presently, almost all pay TV is on this per-channel basis. Examples of the beginners are Home Box Office Co. in Allentown, Pennsylvania, and Optical System in San Diego, California, both in 1972.

The third stage appears when the subscriber is allowed to choose programs he wants and pays an additional charge for them. Since, in this per-program scheme, the subscriber pays only for those programs viewed, it requires some way for the subscriber to communicate his request to the head-end to activate his channel at the proper time. Cablerama in Columbus, Ohio and Via Code in Smithtown, New York, are examples of this two-way system. However, the two-way communication is of limited information.

The development of systems in which signals can be passed up-and downstream without interference with each other, has allowed the complete two-way system to become a reality and all manner of services become possible. There already is an impressive number of experimental two-way systems in operation in the U.S. They represent a variety of approaches: multiplexed single cable, dual cable, switched high-frequency cable, etc. The ultimate value of these test systems is in the determination of the practicality of specific approaches.

A central computer at the head-end terminal manages the amount and
variety of information and control signals that are used in any two-way system. This computer prepares, stores, orders and classifies all the digital information sent to and received from each subscriber terminal, allowing an ordered audio-video and digital interaction between the terminals of the system.

It is the purpose of this thesis to analyze the different ways in which the digital information can be sent to a subscriber, hereafter named, "Question Data Word", and the consequent way in which the digital information is received at the head-end terminal from each subscriber, the "Answer Data Word".

The main parameter analyzed is the total time necessary for interrogating all the subscribers of the system and receiving all the corresponding answers. Each of the methods of interrogation is analyzed in terms of the distribution of subscriber, softwave redundancy, QDW length, ADW length, number of subscribers, etc.
2. **Two-Way CATV Systems**

Even though no real market now exists for two-way CATV systems, many enterprising cable system operators and equipment suppliers are engaged in creating the market through experimentation with two-way systems in the field.

In addition to regular television service, a two-way CATV system can provide many other services, including premium television, restricted television, home protection systems, surveys, meter reading, subscriber response polls, emergency alarms, accessory power control and timing, system diagnostics and control, shopping at home, educational instruction, reservation services, quiz shows, data book access, weather service, scheduled community programs with and without talkback, medical service at home, etc., all under the control of a central computer.

Possible two-way applications are limited only by one's imagination. The particular application of the system will determine which capabilities are to be included.

2.1. **Model**

Figure 2.1 shows a general model of a two-way system using a two-way cable. Depending upon the particular service to be given to the subscribers, some or all of the following devices is attached to the terminals: TV set, audio transceiver and control, TV camera, alphanumeric
Figure 2.1. General two-way CATV system organization.
keyboard, alphanumeric generator with video monitor and/or printer, alarms, meter, etc.

This is one of the first approaches used in the early experimental two-way systems (6) (3), but it is far from being unique. One modification is to use two switchable coaxial cables so that the general communication capability is increased (4). In general, the number of cables is limited only by the cost of installation and by the increase in complexity of the required control systems. This redundancy in cable distribution allows the subscriber to receive different programs in different receivers at the same time (2), which sometimes can be helpful.

High Frequency twisted pairs can be used instead of coaxial cable (5), locating exchange centers every certain amount of subscribers (like with the phone lines).

With few exceptions, existing installations are single-cable. The upstream and downstream signals are transmitted at different frequencies using bidirectional amplifiers (Figure 2.2). The lines are classified in trunk lines, feeder lines and line extenders.

2.2. Frequency Assignment

A typical 1" diameter coaxial cable can carry all the channels shown in Table 2.1 (7). The exact number of channels in operation depends on
Figure 2.2. Two-way single cable system configuration.
<table>
<thead>
<tr>
<th>Channel</th>
<th>Frequency Range (MHz)</th>
<th>Channel</th>
<th>Frequency Range (MHz)</th>
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<tbody>
<tr>
<td>T-7</td>
<td>5.75-11.75</td>
<td>7</td>
<td>174-180</td>
</tr>
<tr>
<td>T-8</td>
<td>11.75-17.75</td>
<td>8</td>
<td>180-186</td>
</tr>
<tr>
<td>T-9</td>
<td>17.75-23.75</td>
<td>9</td>
<td>186-192</td>
</tr>
<tr>
<td>T-10</td>
<td>23.75-29.75</td>
<td>10</td>
<td>192-198</td>
</tr>
<tr>
<td>T-11</td>
<td>29.75-35.75</td>
<td>11</td>
<td>198-204</td>
</tr>
<tr>
<td>T-12</td>
<td>35.75-41.75</td>
<td>12</td>
<td>204-210</td>
</tr>
<tr>
<td>T-13</td>
<td>41.75-47.75</td>
<td>13</td>
<td>210-216</td>
</tr>
<tr>
<td>2</td>
<td>54-60</td>
<td>J</td>
<td>216-222</td>
</tr>
<tr>
<td>3</td>
<td>60-66</td>
<td>K</td>
<td>222-228</td>
</tr>
<tr>
<td>4</td>
<td>66-72</td>
<td>L</td>
<td>228-234</td>
</tr>
<tr>
<td>5</td>
<td>76-82</td>
<td>M</td>
<td>234-240</td>
</tr>
<tr>
<td>6</td>
<td>82-88</td>
<td>N</td>
<td>240-246</td>
</tr>
<tr>
<td>LOW-VHF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>88-108</td>
<td>FM</td>
<td>0</td>
<td>246-252</td>
</tr>
<tr>
<td>88-108</td>
<td></td>
<td>P</td>
<td>252-258</td>
</tr>
<tr>
<td>A</td>
<td>120-126</td>
<td>Q</td>
<td>258-264</td>
</tr>
<tr>
<td>B</td>
<td>126-132</td>
<td>R</td>
<td>264-270</td>
</tr>
<tr>
<td>C</td>
<td>132-138</td>
<td>S</td>
<td>270-276</td>
</tr>
<tr>
<td>D</td>
<td>138-144</td>
<td>T</td>
<td>276-282</td>
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<tr>
<td>MID-BAND</td>
<td></td>
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<tr>
<td>E</td>
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<td>F</td>
<td>150-156</td>
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<td>W</td>
<td>294-300</td>
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<td>H</td>
<td>162-168</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>168-174</td>
<td></td>
<td></td>
</tr>
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Table 2.1 - TV Channel Data (after 10)
the particular system, as well as on the forward and return bandwidths.

In a subsplit system the return signals use the range 5-30 MHz for combinations of audio, video and digital signals, depending on the particular application. In the event that more return channels are necessary, the return bandwidth is extended to 108 MHz (midsplit system), using the proper bidirectional amplifiers. Table 2.2 shows an example of a subsplit system.

2.3. **Subscriber Terminal**

As the system has been defined, all the control is performed at the head-end computer; therefore the digital circuitry at the subscriber site will be passive in the sense that it is not able to send any information to the head-end unless it is requested to do so by means of the QDW. Then, the information goes to the head-end as "status" information. If, for example, a specific program is to be enabled at one of the subscriber terminals; first, the request must be received in response to an interrogation; then, the head-end sends all the necessary control signals.

The more different actions the subscribers are allowed to take, the more complex the subscriber terminal must be. Figure 2.3 shows an example of terminal organization (3). The unit includes a channel
<table>
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<th>Signal</th>
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<th>Range (MHz)</th>
<th># Channels</th>
<th>Modulation</th>
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<tr>
<td>Video</td>
<td>forward</td>
<td>50-300</td>
<td>36</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Video</td>
<td>return</td>
<td>12-50</td>
<td>6</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Audio</td>
<td>forward</td>
<td>on video carrier</td>
<td>36</td>
<td>Frequency</td>
</tr>
<tr>
<td>Audio</td>
<td>return</td>
<td>on video carrier or 5.5-5.6</td>
<td>6+ 3</td>
<td>Frequency</td>
</tr>
<tr>
<td>Digital</td>
<td>forward</td>
<td>110-116</td>
<td>1</td>
<td>FSK*</td>
</tr>
<tr>
<td>Digital</td>
<td>return</td>
<td>6-12</td>
<td>1</td>
<td>PM or PSK**</td>
</tr>
</tbody>
</table>

Table 2.2. Subsplit system. Example

*Frequency Shift Keying

**Phase Modulation or Phase Shift Keying
Figure 2.3. Subscriber Terminal. Example.
converter, an RF receiver section, a crystal-controlled digital transmitter for return signals, and a digital control system.

Each terminal is identified by an ID code which enables the terminal to accept only the QWD code specifically directed to it (Figure 2.4). The content of the word code register determines the action to be taken, i.e. enabling a channel, reading status, starting transmission etc. The Data Register stores the digital information received or that to be returned.

2.3.1 Data Words

The number of bits in the QDW is a function of the number of subscribers in the system (ID code) as well as the complexity of the terminal (Word Code & Data).

For a fixed word-code-data (CD), the cardinality of QDW is:

$$|QDW| = \log_2 N + |WCD|$$  \hspace{1cm} (2.1)

where \(N\) - number of subscribers in the system.

Similarly:

$$|ADW| = \log_2 N + |DATA|$$  \hspace{1cm} (2.2)

It is very common not to send back the ID code, in which case the answers are identified by the order in which they arrive at the head-end,
Figure 2.4. Interrogation and Answer digital word.
Example
necessarily the same as the order in which the interrogations were previously sent. Thus,

\[ |ADW| = |Data| \]

The time used to send one of these data words can be determined for a given feeding rate \( R \) (bits/second) as:

\[ t_Q = \frac{|QDW|}{R} \quad (2.4) \]
\[ t_A = \frac{|ADW|}{R} \]

where \( t_Q \) and \( t_A \) are Question and Answer data word length, respectively.

### 2.3.2 Answering Time and Delay Time

The terminals as described in Figure 2.3 can process only one QDW at a time; therefore, when designing the System care must be taken to avoid overlapping of QDW's by considering the delay time \( \delta R \) for the ADW to be ready after the QDW is received. Defining the answering time \( (t_A) \) as the finite time between the reception of the first bit of the QDW and the emission of the first bit of the ADW, then:

\[ t_R = t_A + \delta R \quad (2.5) \]

The value of \( \delta R \) is mainly determined by the delay time in the preamplifier stage of the terminal.
It must be noted that overlapping of ADW's at the head-end can also be avoided by considering a controlling time $\delta_w$ in the return path.

2.4. Amplifier

The bidirectional amplifier is generally modularized and can be configured in many ways to satisfy specific system requirements.

In the bidirectional mode the forward and return signals must be kept separated. Accordingly, the amplifier case contains built-in filters to separate the downstream from the upstream signals. These diplexing filters are set in conformity with the split of the bandwidth for both paths (subsplit or midsplit).

Most modern amplifiers are two stage amplifiers in order to keep a good relation between gain, noise, figure and cost. AGC return amplifiers are also available.

Redundancy is usually provided, especially for use in the trunk amplifiers. Either power supply or forward amplifier redundancy, or both is installed. Upon failure of either the primary forward amplifier or the primary dc supply module, the respective standby module takes over. Furthermore, the occurrence of a switchover to a standby module will result in an indication (control signal) at the system head-end. The failure information is transmitted to the head-end via the return path.
2.4.1 Amplifier Setting

The setting of the amplifiers in the system is done following the requirements of the system regarding TV channels transmission. It has been determined that for a flawless picture of studio quality, a video signal-to-noise ratio of 40 db is required, and that a 30 db figure would suffice for a very good picture \(^{(9)}\). The amplifier will have a value for the overload level and for its noise figure. The range available for amplifier gain will be determined by the relation of these values in the system. As the system is made up of a cascade of amplifiers, the noise power increases proportionally to the number of amplifiers. On the other hand, the overload level of the amplifiers decreases as the number of amplifiers in cascade increase (Figure 2.5). Consequently the maximum allowed gain per amplifier decreases as the number of cascaded amplifiers increases. Figure 2.6, shows the maximum gain of one amplifier as a function of the number of amplifiers in cascade for fixed signal to noise ratio at the end of the system and using the ratio of overload level to equivalent input noise to describe the quality level of the amplifier. This way of describing the quality of the amplifier makes it reasonably independent of actual gain setting of the amplifier.
Figure 2.5. System derating diagram
Figure 2.6. Maximum Gain per amplifier vs. Number of amplifiers. System S/N constant.
2.4.2 **Optimum Spacing**

Given the S/N ratio for one single stage amplifier, it is degraded for a cascade of \( m \) identical amplifiers as:

\[
(S/N)_m = 10 \log (S/mN) = (S/N)_1 - 10 \log (m) \quad [\text{dB}]
\]

where each identical amplifier contributes with the same amount of noise. The overload level accumulation is expressed with a similar equation as:

\[
\phi_m = \phi_i + 10 \log (m) \quad [\text{dB}]
\]

Therefore the amplifier dynamic range is derated by a value \( 20 \log (m) \) for a cascade of \( m \) single-stage identical amplifiers, and the maximum gain per amplifier is expressed as:

\[
G = G_0 - 20 \log (m) \quad (2.6a)
\]

Figure 2.6 shows \((2.6a)\) with \( C_1 = 10^{G_0/20} \). Since for each number of amplifiers there is a particular maximum gain setting, the system length varies as:

\[
L (\text{db}) = m \cdot G (\text{db})
\]

From \((2.6)\) the number of amplifiers is

\[
m = 10^{(G_0 - G)/20} \quad (2.7a)
\]
Thus,\[ L = G \cdot 10^{(Go-G)/20} \] (2.8)

(2.8) has a maximum value, named maximum system length ($L_{\text{max}}$), at a gain value that is determined as:

\[ \frac{dL}{dG} = e^{2.303(Go-G)/20} \cdot \frac{G-2.303}{20} \cdot e^{2.303(Go-G)/20} = 0 \]

thus:

\[ 1 - \frac{G \cdot 2.303}{20} = 0 \]

\[ Go_{\text{opt}} = 8.684 \text{ db} \] (2.9)

Hence, the optimum spacing for a one stage amplifier in cascade is a constant value. It is important to note that in the determination of (2.9) it is implicitly assumed that the overload and noise levels of the amplifier are independent of the gain setting, such that the optimum spacing becomes independent of these values.

Considering two stages amplifiers, the total output power depends on the individual contributions of each stage as (11):

\[ \frac{1}{P_{s0}} = \frac{1}{P_{s1}} + \frac{1}{P_{s2}} \]

then:

\[ P_{s0} = \frac{P_{s1} \cdot P_{s2}}{P_{s1} + P_{s2}} \]

but the maximum values are determined by the overload levels and the gain setting ($A_1, A_2$) for each stage, so that:

\[ P_{s1} = \phi_1 A_2 \quad ; \quad P_{s2} = \phi_2 \]
replacing:

\[ P_{\text{so}} = \frac{\phi_1 \phi_2 A_2}{\phi_1 A_2 + \phi_2} \]

and for \( m \) identical amplifiers in cascade:

\[ P_{\text{so}_m} = \frac{\phi_1 \phi_2 A_2}{(\phi_1 A_2 + \phi_2)^m} \]

Similarly, given the equivalent input noise per stage \((N_1, N_2)\), the total output noise power is:

\[ P_{\text{no}} = N_1 A_1 A_2 + N_2 A_2 \]

and for \( m \) identical amplifiers:

\[ P_{\text{no}_m} = (N_1 A_1 A_2 + N_2 A_2)^m \]

Thus the dynamic range:

\[ K = \frac{P_{\text{so}_m}}{P_{\text{no}_m}} = \frac{\phi_1 \phi_2}{(\phi_1 A_2 + \phi_2)(N_1 A_1 + N_2)^m} \]

the length of the system is now:

\[ L = (A_1 A_2)^m \quad (2.8 \text{b}) \]

from where:

\[ m = \frac{\ln (L)}{\ln (A_1 A_2)} \quad (2.7 \text{b}) \]

and replacing:

\[ K = \frac{\phi_1 \phi_2 \ln^2 (A_1 A_2)}{(\phi_1 A_2 + \phi_2)(N_1 A_1 + N_2) \ln^2 (L)} \]

to obtain the optimum spacing, it is necessary to maximize \( K \) as a function of both \( A_1 \) and \( A_2 \); that is:

\[ \frac{\partial K}{\partial A_1} = \frac{\partial K}{\partial A_2} = 0 \]
This process leads to the following equations:
\[
\ln A_2 = 1 + \frac{\Phi}{A_2} - \frac{1}{2} \ln \left( \frac{N}{\Phi} \right)
\]
(2.10)
where:
\[
A_1 = \frac{N A_2}{\Phi} \quad ; \quad \Phi = \frac{\Phi_2}{\Phi_1}
\]
If the two stages are identical, \( A_1 = A_2 = A \), \( \Phi_1 = \Phi_2 \)
\[
\ln A = 1 + \frac{1}{A_2}
\]
from where \( A = 3.59 \) Then,
\[
G_{opt} = A^2 = 12.89 = 11.1 \text{ db}
\]
If the second stage has higher overload level, i.e. 6 db increased noise
and overload level, then from
\[
G_{opt} = 15 \text{ db}
\]
Various other cases can be calculated, but the more important
practical amplifiers are likely to fall somewhere in between. For every
particular amplifier, optimum spacing may be determined directly from
the measured amplifier characteristics, even though optimum spacing, as
well as amplifier dynamic range, should be part of the specification of
every CATV amplifier. Figure 2.7 shows the variation of the system length
vs. the amplifier gain for the three cases considered.

2.4.3 Cable

The classical transmission line is the coaxial cable, which has
excellent characteristics in bandwidth, transmission constant and physical
resistance.
Figure 2.7. Per cent of System length vs. Amplifier gain. Optimum spacing.
Since the attenuation of coaxial cable increases with the frequency, the length of cable between amplifiers is fixed by equalizing the attenuation at the highest frequency with the gain setting of the amplifier. Figure 2.8 shows a qualitative view of the variation of cable attenuation with frequency. The relation cable attenuation - amplifier gain is shown in Figure 2.9, for a 17db spacing. The cable attenuation also varies with the temperature, but enough range in the AGC amplifiers on the line should take care of this variation.
Figure 2.8. Cable Attenuation vs. Frequency.
Figure 2.9. Matching amplifier gain with cable attenuation vs. frequency. 17 db spacing.
3. Delay

Since the transmission velocity through the cable is finite, there will be a finite time spent by the signal traveling in the cable. This finite time, expressed as cable delay per unit of length, can be considered constant under constant temperature.

Also there is an amplifier delay, that is constant for similar amplifiers, similarly balanced in the system. Under these definitions, we can talk about spacing delay as:

$$t_D = d_A + S \cdot d_C$$

(3.1)

where:

- $d_A =$ amplifier delay
- $S =$ spacing length
- $d_C =$ cable delay per unit of length

In practice the separation between amplifiers is usually not exactly the designed spacing; however, it is assumed that, on the average, the actual spacing approximates the calculated one and that the variations are small enough so that they will not introduce significant error when using the theoretical value in the analysis.

Taking the first bit of the QDW and the first bit of the ADW at the head-end terminal as references, the total time used in interrogating $N$ subscribers in a system can be determined from the parameters already defined.
3.1. **Delay Distribution**

The distribution of subscribers along the line varies considerably from system to system, complicating the generalization of the problem.

Instead of considering the physical location of subscribers with respect to the head-end (i.e. density), their "electrical" location can be determined by taking their delay-distance from the head-end; thus, each terminal will have a delay value attached that completely describes its location. Note that there may be terminals located at the same delay-distance from the head-end, even though they are not at the same physical position.

In what follows, there is no need to fit these values to a mathematical expression because all the parameters involved can be readily determined from the terminal-delay distribution data. In particular, the information required is: the maximum delay in the system \((D_m)\), the average delay \((D_{av})\) and the total number of terminals \((N)\). Further, in some cases it will be necessary to know the number of terminals whose delay-distance is within a given range \((D_u < D < D_v)\) and the average delay among these values \((D_{av_i})\).
3.2. **Maximum Delay In The System (D_n)**

It should be recalled from (2.41) that there is an optimum spacing for any given amplifier and that for spacings different from the optimum the numbers of amplifiers in the system will also change. Therefore, once the amplifier characteristics are determined, the maximum delay in the system is a function only of the system length.

Recalling that \( m \) is the number of amplifiers in the longest path in the system, it will be the number of spacings between the head-end and the farthest subscriber. According to the distribution function already chosen there are subscribers at all the delay distances, therefore, the maximum delay is given by:

\[ D_n = m \cdot t \]  

or:

\[ D_n = m \left( d_A + S \cdot d_C \right) \]  

For a given fraction of maximum system length, the spacing (G) is determined from Figure 2.7, \( m \), from Figure 2.6, and the spacing length (S) from the known cable attenuation (ATT) as:

\[ S = \frac{G}{ATT} \]  

replacing (3.12) in (3.11)

\[ D_n = m \left( d_A + \frac{G}{ATT} \cdot d_C \right) \]
This method shall be followed in any analysis of the system. However, in order to make the comparison the system is assumed as using two-identical-stages amplifiers, so that $G_{\text{opt}} = 11 \text{ db}$. Taking $G_{\text{opt}}$ as a lower bound for the gain, it can be seen that $L$ will decrease only for increasing $G$ (Figure 2.7). The curve in Figure 2.7 may be approximated by a straight line fitted through the points $(11 \text{ db}, 1)$ and $(15 \text{ db}, 0.9)$, where the second point has been estimated. Hence, the equation becomes:

$$\Delta L = -0.025 \cdot G + 1.28 \quad (3.14)$$

so:

$$G = \frac{\Delta L - 1.28}{-0.025} = \frac{1.28 - \Delta L}{0.025} \quad (3.15)$$

and from (3.12):

$$S = \frac{1.28 - \Delta L}{0.025 \cdot \text{ATT}} \quad (3.16)$$

Replacing (3.16) and (3.11):

$$D_N = m \left( dA + \frac{(1.28 - \Delta L) \cdot dC}{0.025 \cdot \text{ATT}} \right) \quad (3.17)$$

Assuming a straight line for $G$ vs. $m$ as shown in Figure 2.6, from (2.8a)

$$L = G \cdot 10^{(G_{0} - G)/\log C} \quad (3.18)$$
This equation should have a maximum at \( G = 11 \text{ db} \); thus,

\[
\log C_i = \text{Go}_{\text{pt}} \times 2.303 \approx 26
\]

therefore:

\[
m = 10 \frac{(\text{Go} - G)/26}{n}
\]

replacing: (3.15) in (3.19):

\[
m = 10 \frac{1}{26} (\text{Go} - \frac{1.28 - \Delta L}{0.025})
\]

and finally, replacing (3.20) in (3.17):

\[
D_{\text{av}} = 10 \frac{1}{26} (\text{Go} - \frac{1.28 - \Delta L}{0.025}) \left[ dA + \frac{(1.28 - \Delta L)}{0.025} \frac{dC}{AA_{\text{av}}} \right]
\]

where; \( \text{Go} \) = maximum gain of one amplifier

3.3. **Delay Per Terminal (Dt) And Average Delay (Dav)**

The delay-value attached to each terminal is determined from the known spacing delay (3.1) as:

\[
Dt = m_i \cdot t_D
\]

where; \( m_i \) = number of spacings between the head-end and terminal

Since there \( n_t \) terminals located at the same delay-distance \( Dt \), the average delay for the systems becomes:

\[
D_{\text{av}} = \frac{\sum n_t \cdot Dt}{N}
\]

where; \( N \) = total number of terminals in the system.

Similarly, the average delay corresponding to any section of the delay distribution whose delay-values are greater or less than some given value
Dk may be calculated as:

\[ D_{av_k} = \begin{cases} \sum \frac{n t \cdot D_t}{K} & D_t > D_k \\ \sum \frac{n t \cdot D_t}{K} & D_t < D_k \end{cases} \quad (3.23) \]

where:

\[ K = \sum n t \]

is the number of terminals whose delay is greater or less than Dk.
4. **Interrogation Time**

The total interrogation time \( T \) is defined as the total time spent in sending an \( QDW \)'s and receiving the corresponding an \( ADW \)'s. The \( a \) term stands for software redundancy; in other words, each \( QDW \) will be sent \( a \) times to each subscriber in order to increase reliability in the answer.

Physically, \( T \) is the time interval from the instant the first bit of the first \( QDW \) is just coming out of the head-end output terminals to the instant the last bit of the last \( ADW \) has just been received at the head-end.

4.1. **First Method, Question by Question**

In this method, each \( QDW \) is sent right after the \( ADW \) corresponding to the previous \( QDW \) received. Then, the delay attached to the subscriber \( (D_i) \) can be defined as half the total time between the emission of the first bit of \( QDW_i \) at the head-end output terminals and the reception of the first bit of \( ADW_i \) at the head-end. Mathematically:

\[
D_i = \frac{1}{2} \left( 2m_i t_B + t_A \right) \quad (4.1)
\]

Where:
- \( m_i \) = number of spacings between the head-end and terminal;
- \( t_B \) = spacing delay (Eq. 3.1);
- \( t_A \) = terminal answering time. (Eq. 2.5)

Since the head-end waits for the answer to the previous question
before sending the next question, the pause between QDW's, named \( t_{\Delta A} \) will be:

\[
t_{\Delta A} = 2D_{i-1}
\]

(4.2)

for different subscribers, and

\[
t_{\Delta A} = 2D_i
\]

(4.3)

for the same subscriber (recall that there is a redundancy \( a \)).

Therefore, the total interrogation time \( (T_i) \) is:

\[
T_i = \sum a (2D_i + t_A)
\]

(4.4)

or

\[
T_i = aNt_A + 2a \sum D_i
\]

(4.5)

where the ADW length has been included, showing that the entire answer must be received before the next question is sent.

For a known delay distribution, the summation \( (\sum) \) term, may be eliminated from (4.5) by substituting the average delay (§ 3.3):

\[
2 \sum D_i = 2N D_{av} + N t_A
\]

(4.6)

to obtain:

\[
T_i = aNt_A + 2aN D_{av} + aN t_A
\]

and applying (2.5)

\[
T_i = aN (t_A + t_A + t_A + 2D_{av})
\]

(4.7)

However, the pause between ADW \( (t_{\Delta A}) \) has to be at least equal to the
resolution time at the head-end ($\delta_h$), so that $t_A$ has to be recalculated accordingly. The relationship between pauses can be expressed as:

(Figure 4.4)

\[ t_{AQ} - t_{AA} = t_A - t_Q \quad (4.8) \]

so that if $t_{AA}$ is to be chosen to be exactly $\delta_h$, then:

\[ t_{AQ} = t_A - t_Q + \delta_h \]

but by definition of the method, $t_{AQ}$ is given by (4.2) and (4.3). Thus, since (4.8a) cannot be always fulfilled, the required value of $t_{AQ}$ may be expressed in terms of a reference terminal at a delay, $D_j$; where:

\[ 2D_j = t_A - t_Q + \delta_h \quad (4.8b) \]

such that

\[ t_{AQ} = t_A - t_Q + \delta_h \quad \text{for} \quad D_i < D_j \]

\[ t_{AQ} = 2D_i \quad \text{for} \quad D_i > D_j \quad (4.9) \]

Therefore, (4.7) is valid only if the closest terminal has a delay $D_j$. Another particular solution for $T_i$ occurs in case that:

\[ 2D_m + t_k < 2D_j \quad (4.10) \]

min is given by (4.9a), and the total interrogation time becomes:

(Figure 4.1)

\[ T_i = (\alpha N - 1)(t_Q + t_{AQ}) + 2D_j + t_A \]

where $D_j$ is the delay to the last terminal interrogated; assuming that
Figure 4.1. Determination of total interrogation time. Method I.
the last terminal interrogated is located at the maximum delay then:

\[ 2D_j = 2D_n + t_Q + 5R \]

and \( T_1 \) becomes:

\[ T_1 = aN \cdot t_A + t_Q + (aN-1)5_H + 5R + 2DN \tag{4.11} \]

A more general result is available for \( T_1 \). Naming \( K_1 \) the number of subscribers whose delay is less than \( D_j \), the total interrogation time for Method I becomes:

\[ T_{1z} = [aK_1 \cdot t_A + t_Q + (aK_1-1)5_H + 5R + 2D_j] + \]

\[ + [a(N-K_1)(t_A+t_Q+5R+2D_{av_1})] \tag{4.12a} \]

where the first term represents terminals "closer than" \( D_j \) for which the maximum \( \tau_Q \) is 2 \( D_j \), and the second term represents terminals for which is determined solely by waiting for the answers. \( D_{av_1} \) is the average delay for the terminals "farther than" \( D_j \). Rearranging:

\[ T_{1z} = AN \cdot t_A + (aN+1) t_Q + (aN+1)5_R - 5_H + aN(2D_{av_1}) + 2D_j + \]

\[ -aK_1(5_R - 5_H + t_Q + 2D_{av_1}) \tag{4.12a} \]

Further, it shall be noted that \( \tau_Q \) cannot be less than \( 5R \), because all the QDW's pass through each terminal for ID checking. Thus, (4.15a) applies if, \( t_A - t_Q + 5_H \geq 5R \); if not,

\[ \tau_Q = 5R \quad ; \quad \tau_A = 5R + t_Q - t_A \]
Hence,

\[ T_{ii} = [(aK_i - 1)(t_Q + \delta_k) + 2D_j + t_Q + \delta_k + t_A] + \]

\[ + [a(N-K_i) (t_A + t_Q + \delta_k + 2D_{av})] \]

and rearranging:

\[ T_{ii} = (aN + 1)t_A + an t_Q + aN \delta_R + aN (2D_{av}) + 2D_j + \]

\[ - aK_i (t_A + 2D_{av}) \]  \hspace{1cm} (4.12b)

Note here that (4.12a) and (4.12b) are symmetrical if the forward and return paths are symmetrical, i.e., \( \delta_R = \delta_A \).

This method offers the advantage that the equipment needed to control the order and timing of the interrogation process is quite simple, implying low cost.

4.2. Second Method. Questions In Stream

A second method of operating the system consists of sending the questions one after the other with a minimum possible pause (\( t_{AQ} \)) between them. Now, the head-end computer has to control \( t_{AQ} \) and the order in which questions are sent and recognize the answers as received. It is assumed that the addresses (ID code) for the subscribers have been sorted by delay and the interrogation follows that order.
4.2.1 Pause Between QDW's

As it was mentioned before, each terminal is interrogated \( n \) times; therefore, the time between question replications must be sufficient to permit the previous reply to leave the terminal.

In order to fulfill this condition, (Figure 4.2)

\[ t_{AQ} + t_q = t_R + t_A \]

so:

\[ t_{AQ} = t_R + t_A - t_q \quad (4.13a) \]

but \( t_R = \delta_R + t_q \) (see § 2.3.2), then:

\[ t_{AQ} = \delta_R + t_A \quad (4.13b) \]

The pause between ADW is then:

\[ t_{AA} = \delta_R + t_q \quad (4.14) \]

these are the minimum values; therefore, including guard time the equations become:

\[ t_{AQ} = \delta_R + t_A + t_G \]

\[ t_{AQ} = \delta_R + t_A + t_G \quad (4.15) \]

The minimum pause between QDW (\( t_{AQ} \)) for different terminals becomes limited by \( \delta_R \), the delay at the subscriber terminal, for every QDW passes through the terminal for ID checking. Furthermore, the minimum pause between ADW (\( t_{AA} \)) is limited by the resolution time at the head-end \( \delta_H \).

Hence,

\[ t_{AQ} \geq \delta_R \quad ; \quad t_{AA} \geq \delta_H \quad (4.16) \]
Figure 4.2. Determination of $t_{AQ_i}$. Method II

$t_1 = t_{AQ} + t_Q = t_R + t_A$
However, both minimum values do not necessarily occur simultaneously.

If one fixes:

\[ t_d = \delta_R \quad (4.17a) \]

then \( t_d \) becomes: (Figure 4.3a)

\[ t_d = \delta_R + t_q - t_a \quad (4.17b) \]

but \( t_d \) must be \( \geq \delta_H \), so that from (4.17b), it should be:

\[ \delta_R + t_q - t_a \geq \delta_H \]

or:

\[ t_q - t_a \geq \delta_H - \delta_R \quad (4.18a) \]

On the other hand, if (4.18a) is not satisfied, then \( t_d \) has to be chosen to be at least as large as \( \delta_H \),

\[ t_d = \delta_H \quad (4.18a) \]

in which case, \( t_d \) becomes: (Figure 4.4)

\[ t_d = t_a - t_q + \delta_H \quad (4.18b) \]

and since \( t_d \) must be \( \geq \delta_R \), then:

\[ t_a - t_q + \delta_H \geq \delta_R \]

or:

\[ t_q - t_a \leq \delta_H - \delta_R \quad (4.18b) \]

which is merely a restatement of (4.18a) unsatisfied. Therefore, if one is to assume minimum values the following conditions apply:
Figure 4.3. Determination of $t_{AQ_i}$. Method II
Figure 4.4. Determination of $t_{\Delta \alpha}$. Different terminals. Method II.
For $t_q-t_a > \delta H - \delta R$

\[ t_{AQ \text{min}} = \delta R \]
\[ t_{AA \text{min}} = \delta R + t_q-t_a \]  \hfill (4.17)

For $t_q-t_a < \delta H - \delta R$

\[ t_{AQ \text{min}} = \delta H - t_q + t_a \]
\[ t_{AA \text{min}} = \delta H \]  \hfill (4.19)

For $t_q-t_a = \delta H - \delta R$

\[ t_{AQ \text{min}} = \delta R \]
\[ t_{AA \text{min}} = \delta H \]  \hfill (4.20)

In general (4.17) (4.19) (4.20) can be expressed as:

\[ t_{AA} - t_{AQ} = t_q-t_a \]  \hfill (4.21)

4.2.2 Total Interrogation Time Determination

From Figure 4.5, $T_2$ becomes:

\[ T_2 = t_q \left[ a(N-1) + (a-1) \right] + t_{AQ} \left[ (N-1)(a-1) + (a-1) \right] + (N-1)t_{AQ} + \]
\[ t_{R} + t_a + 2DN \] \hfill (4.22)

Substituting $t_{AQ}$ and $t_R$ by their values: (4.13) (2.5)

\[ T_2 = (N-1)t_{AQ} + aNt_a + t_a \left[ N(a-1) + 1 \right] + \delta R \left[ N(a-1) + 1 \right] + 2DN \]  \hfill (4.23)

Assuming that (4.17) holds:

\[ T_21 = aNt_a + t_a \left[ N(a-1) + 1 \right] + \delta R aN + 2DN \]  \hfill (4.23)

On the other hand, if (4.19) holds:

\[ T_22 = t_q \left[ N(a-1) + 1 \right] + aNt_a + \delta R \left[ N(a-1) + 1 \right] + \delta H (N-1) + 2DN \]

If the forward and return paths are symmetrical i.e., $\delta_R = \delta_H$, (4.23) and (4.24) become symmetrical also. Furthermore, if the affect of $t_{AQ}$ is deleted by making $a = 1$, then $T_21 = T_22 = T_2$. However, since the analysis should be kept in general form, both values shall be considered when
Figure 4.5. Determination of total interrogation time.
Method II.
comparing the interrogation time with other methods.

This method (either case) is faster than Method I; however, it is also more expensive, not only because of the equipment needed to control the order and timing of the interrogation process, but also because of the pre-processing required to sort and store terminal addresses by delay.

4.3. Third Method. Combination

A combination of the first and second methods consists of sending the a repetitions to a terminal; then waiting for the answers before sending the next a repetitions to the next terminal.

4.3.1 Pause Between QDW's

The pause between QDW's for the same terminal (tAQ_i) remains that given by (4.13). The pause between QDW's for different terminals (tAQ) has to be recalculated, however.

When analyzing the first method, the "signal" (for terminals farther away than Dj) for sending the next QDW was that the ADW corresponding to the last QDW sent had been received. Assuming that the "signal" to send QDW_{i+1} is the reception of the first ADW1 (out of a), tAQ becomes (Figure 4.6)
Figure 4.6. Determination of $\tau Q_i$. Method III. First approach
\[ t\Delta Q = 2D_i - a t_A \quad (4.25) \]

Substituting (4.13):

\[ t\Delta Q = 2D_i - (a-2)t_A - (a-1)\delta R - a t_Q \quad (4.26) \]

It is clear that to avoid overlapping of QDW's, (4.16) has to be satisfied. Thus, it must be:

\[ 2D_i - (a-2)t_A - (a-1)\delta R - a t_Q \geq \delta R \]

or:

\[ 2D_i \geq (a-2)t_A + a(t_Q + \delta R) \triangleq 2D_k \quad (4.27) \]

Since (4.27) cannot be always satisfied, there are two values for \( t\Delta Q \), namely:

\[ t\Delta Q = 2D_i - (a-2)t_A - (a-1)\delta R - a t_Q \quad \text{for} \quad 2D_i > 2D_k \quad (4.28) \]

and

\[ t\Delta Q = \delta R \quad \text{for} \quad 2D_i \leq 2D_k \quad (4.29) \]

In this case, the total interrogation time \( T_3 \) is a function of the system parameter \( D_k \), which depends upon the particulars of \( t_Q \), \( t_A \) and \( \delta R \). This dependence is a consequence of the decision to transmit the next QDW before the receipt of all the ADW's corresponding to the previous QDW. If, however, the next QDW is sent only after all the ADW's from the previous set are received (a of them), then an upper bound for \( T_3 \) may be determined. Hence, as shown in Figure 4.7:

\[ t\Delta Q = 2D_i + a(t_A - t_Q) + (a-1)(t\Delta A_i - t\Delta Q_i) \]

51
Figure 4.7. Determination of $t_{\alpha \alpha}$. Method III. Upper bound.
Substituting from (4.13) (4.14)

\[ t_{DA} = 2D_i - (tA - tA) \]  
(4.30)

and from (4.8) the pause between ADW's is:

\[ t_{DA} = tAQ + (tQ - tA) = 2D_i \]  
(4.31)

but \( t_{DA} \) has to be at least \( \delta W \), so that it should be:

\[ 2D_i \geq \delta W \]  
(4.32)

This equation cannot always be satisfied; therefore, \( tAQ \) shall be re-defined as given by (4.17) (4.19) (4.20) for \( 2D_i < \delta W \), and by (4.30) for \( 2D_i \geq \delta W \).

4.3.2 Total Interrogation Time Determination

The total interrogation time can be determined as: (Figure 4.8)

\[ T_3 = \sum a_i tQ + (a-1) tAQ + tAQ \]  
(4.31)

Applying (4.13b) and (4.30), and rearranging:

\[ T_3 = (a-1)N (tQ + \delta R) + aN tA + \sum_1^N 2D_i \]  
(4.32)

Substituting (4.6) as:

\[ 2 \sum_1^N D_i = 2N D_{av} + N (tQ + \delta R) \]

(4.32) becomes:

\[ T_3 = aN (tQ + \delta R + tA) + 2N D_{av} \]  
(4.33)

This solution is valid only if the closest terminal has a delay \( \geq \delta W/2 \). The general solution for \( T_3 \) can be determined by considering the
Figure 4.8. Determination of total interrogation time. Method III

\[ t_1 = at\alpha + (a-1) t_{\Delta \alpha i} + t_{\Delta \alpha} \]

\[ t_2 = \sum_{i=1}^{N} at\alpha + (a-1) t_{\Delta \alpha i} + t_{\Delta \alpha} \]
number of subscribers, $K_3$, whose delay is less than $\delta_H/2$; such that, if (4.17) is satisfied, the total interrogation time is:

$$T_{31} = [(aK_3t_q + ta)(K_3(a-1) + 1) + aK_3\delta_R + \delta_H] +$$

$$+ [a(N-K_3)(t_q + \delta_R + ta) + 2(N-K_3)\text{Dav}_3]$$

(4.34)

where $\text{Dav}_3$ is the average delay for the terminals "farther than".

Rearranging (4.35):

$$T_{31} = \alpha N t_a + (aN+1)ta + aN\delta_R + \delta_H + 2N\text{Dav}_3 +$$

$$- K_3(t_a + 2\text{Dav}_3)$$

(4.35)

Similarly, if (4.17) is not satisfied:

$$T_{32} = (aN+1)t_a + aNta + (aN+1)\delta_R + 2N\text{Dav}_3 +$$

$$- K_3(\delta_R - \delta_H + t_a + 2\text{Dav}_3)$$

(4.36)

Note here that both equations are symmetrical whenever $\delta_R = \delta_H$.

This method offers an alternative speed-cost trade-off. The equipment needed to control the order and timing of the interrogation process is as simple as in Method I, but the interrogation speed can be increased several times, with the advantage over the second method that the terminal's addresses do not have to be sorted by delay.
4.4. **Fourth Method. Questions in Stream With Block Grouping**

The following method is proposed in order to avoid the necessity for sorting the terminal addresses by delay.

In the delay distribution, the delay values are grouped in \( M \) equal width sections (Figure 4.9). The group of terminals whose delay falls within the limits of the section \( m \) constitutes the block \( m \). Then, the blocks are arranged in order of delay such that no terminal in block \( m+k \) is interrogated before any members of block \( m \), but the terminals belonging to the block \( m \) can be interrogated in any order. In order to assure that order within a block is immaterial, \( t_{AQ} \) must be made sufficiently large.

4.4.1 **Pause between QDW's**

The pause between QDW for the same terminal is still given by (4.13b) as:

\[
\hat{t}_{AQ} \geq \delta_t + t_A
\]

On the other hand, the pause between QDW for different terminals in the same block (\( t_{AQm} \)), can be derived by taking the worst case; namely, consecutive interrogation of the farthest and then the nearest terminal in a block. Thus, (Figure 4.10):

\[
t_{AQm} - t_{AQm} = a (t_A - t_A) + (a-1) (t_{AQi} - t_{AQi}) + 2 t_B \quad (4.37a)
\]
Figure 4.9. Delay distribution of terminals. Block definition.
Figure 4.10. Determination of \( t_{\Delta a} \). Blocks in stream. Method IV.

\[
t_i = at_0 + (a-1) \tau_{\Delta A_i} + \tau_{\Delta A} + tr \\
\]

\[
t_i' = 2tb + tr + at_0 + (a-1) \tau_{\Delta A_i} + \tau_{\Delta A_m}
\]
substituting $\tau_{AI}$; and $\Delta A_i$:

$$t_{Qm} - t_{Dm} = t_A - t_A + 2 t_B$$  \hspace{1cm} (4.37b)

The minimum pause between QDW and ADW are given by (4.16) as:

$$t_{Qm} > \delta R \quad ; \quad t_{\Delta A} > \delta H$$  \hspace{1cm} (4.16)

If $t_{Qm}$ is fixed as: $t_{Qm} = \delta R$; then from (4.37b):

$$t_{\Delta A_m} = t_{Qm} + t_A - t_A - 2 t_B$$

$$t_{\Delta A_m} = \delta R - 2 t_B + t_A - t_A$$

but accordingly with (4.16), it has to be:

$$\delta R - 2 t_B + t_A - t_A > \delta H$$

or:

$$t_A - t_A > \delta H - \delta R + 2 t_B$$ \hspace{1cm} (4.38a)

If (4.38a) does not hold, $\Delta A$ may be fixed as: $\delta A_m = \delta H$; in which case, from (4.37b):

$$t_{Qm} = \delta H + t_A - t_A + 2 t_B$$

and it has to be:  \hspace{1cm} (4.16)

$$\delta H + t_A - t_A + 2 t_B > \delta R$$

or:

$$\delta H - \delta R + 2 t_B > t_A - t_A$$ \hspace{1cm} (4.38b)

which holds when (4.38a) does not. In conclusion:

For  \hspace{1cm} $t_A - t_A > \delta H - \delta R + 2 t_B$

$$t_{Qm \min} = \delta R$$ \hspace{1cm} (4.39)

$$t_{\Delta A_m \min} = \delta R + (t_A - t_A) - 2 t_B$$
For \( t_q - t_a < \delta_H - \delta_R + t_b \)

\[
\begin{align*}
\Delta Q_m &= \delta_H - (t_q - t_a) + 2t_b \\
\Delta A_m &= \delta_H \\
\end{align*}
\]

(4.40)

For \( t_q - t_a = \delta_H - \delta_R + 2t_b \)

\[
\begin{align*}
\Delta Q_m &= \delta_R \\
\Delta A_m &= \delta_H \\
\end{align*}
\]

(4.41)

and:

\[
\Delta Q_m - \Delta A_m = t_a - t_b + 2t_b
\]

(4.37)

4.4.2 Pause Between QDW For Different Blocks \( (\Delta Q) \)

The worst case (largest) value for \( \Delta Q \) occurs when consecutively interrogating the farthest terminal of one block and then the closest terminal of the next farther block. This condition is in fact, the same as that previously calculated for the maximum variation within a block \((4.39) (4.40)\). Hence,

\[
\Delta Q = \Delta Q_m
\]

4.4.3 Total Interrogation Time Determination

The total interrogation time \((T_q)\) is determined as: \((\text{Figure 4.11})\):

\[
T_q = \sum_{i=1}^{M-1} \left\{ \Delta Q + K_m [(a-1) \Delta Q_i + a \Delta Q] + (K_m - 1) \Delta Q_m \right\} + \\
+ K_m [(a-1) \Delta Q_i + a \Delta Q] + (K_m - 1) \Delta Q_m + 2D_N - t_q + t_a + t_r
\]

where: \(K_m = \text{number of terminals in the block } m\)

\(K_M = \text{number of terminals in the farthest block (block } M)\)
Figure 4.11 Determination of total interrogation time.
Method IV.

$\text{Dwij} =$ data word $j$ of block $i$

$K_m =$ # terminals in block $m$

$t_1 = t_{AQ} + K_m [(a-1) t_{AQ} + a_t q] + (k_m-1) t_{AQ} m$

$t_2 = \sum_{i=1}^{M-1} (t_1)$

$t_3 = t_2 + K_m [(a-1) t_{AQ} + a_t q] + (k_m-1) t_{AQ} m - t_{AQ}$

$t_4 = t_3 + 2M t_B + t_R + t_A = t_3 + 2D_N + t_A + t_R$
$D_N$ has been included, taking the worst case, namely that the last terminal interrogated is the farthest terminal. Since $\sum_{i=1}^{M} k_m t_A q = t_{AQ}$,

$$T_4 = \sum_{i=1}^{M} k_m t_A q + \sum_{i=1}^{M} k_m \left[ (a-1) t_{AQ} + a t_A \right] + 2 D_N - t_q + t_A - t_{AQ} + t_R$$

by definition, $\sum_{i=1}^{M} k_m = N$, therefore:

$$T_4 = (N-1) t_{AQ} + N (a-1) t_{AQ} + N a t_A + 2 D_N - t_q + t_A + t_R$$

Substituting $t_{AQ}$ by (4.13b) and $t_R = t_Q + \delta_R$

$$T_4 = (N-1) t_{AQ} + N (a-1) t_{AQ} + [N(a-1) + 1] t_A + a N \delta_R + 2 D_N \quad (4.42)$$

There are two values of $T_4$ corresponding to the two possible minimum values of $t_{AQ}$. Therefore, for $t_{AQ} = \delta_R$, (4.49) (4.51):

$$T_{41} = a N t_A + [N(a-1)+1] t_A + a N \delta_R + 2 D_N \quad (4.43)$$

and for $t_{AQ} = \delta_H - (t_A - t_A) + 2 t_e$:

$$T_{42} = [N(a-1)+1] t_A + a N t_A + a N \delta_R + (N-1)$$

It should be clear that (4.43) is identical to (4.23), which implies that if (4.39) (4.51) holds, the width of the blocks is so small (number of blocks so large) that sorting the blocks by delay is the same as sorting the terminals, and $T_4$ becomes $T_2$. Therefore, block grouping has meaning only for the condition given in (4.40) and the total interrogation time becomes:

$$T_4 = [N(a-1)+1] t_A + a N t_A + a N \delta_R + (N-1) \delta_H + 2 D_N + (N-1) 2 t_B$$

and since $t_B = D_N / M$

$$T_4 = [N(a-1)+1] t_A + a N t_A + a N \delta_R + (N-1) \delta_H + 2 D_N \left(1 + \frac{N-1}{M}\right) \quad (4.44)$$
and the minimum values of pause are:

\[ t_{\Delta Q_{\text{min}}} = \delta_n + t_A - t_Q + 2t_B \]
\[ t_{\Delta A_{\text{min}}} = \delta_H \]  \( (4.40) \)

4.5. Fifth Method, Combination, Blocks

Another method can be defined which is a combination of waiting and streaming. In this case, all the RTR's of the block are interrogated and all the corresponding answers are received before interrogating any other block.

4.5.1 Pause Between QDW's

The limits already given for \( t_{\Delta Q_i} \) and \( t_{\Delta Q_m} \) under Method IV still hold, because this part of the process does not change; however, \( t_{\Delta Q} \) has to be recalculated as: (Figure 4.12)

\[ t_{\Delta Q} = 2t_m + T_m \]  \( (4.45) \)

where:

- \( t_m = \) delay-distance from head-end to the nearest terminal in block \( m \)
- \( T_m = \) Total interrogation time for the block \( m \), given as:

\[ T_m = (m-1)[a t_Q + (a-1) t_{\Delta Q_i} + t_{\Delta Q_m}] + (a-1)(t_Q + t_{\Delta Q_i}) + 2t_m + t_A + t_K \]

- \( t_m^+ = \) delay-distance from head-end to the farthest terminal in block \( m \).

By definition of the block division:

\[ t_m^- = (m-1) t_B \]
\[ t_m^+ = n t_B \]

Thus,
Figure 4.12. Determination of $t_{AQ}$. Method V
\[ T_m = (Km - 1)[a_{AQ} + (a - 1) t_{AQ} + t_{AQm}] + (a - 1) (t_Q + t_{AQ} + 2m + t_A + t_R) \]

applying (4.13b) and \( t_R = t_Q + \delta_R \)

\[ T_m = (Km - 1) t_{AQm} + Km [a_{AQ} + (a - 1) t_A + (a - 1) \delta_R] + \delta_R + t_A + 2m + t_B \]  
(4.47)

Therefore,

\[ t_{AQ} = (Km - 1) t_{AQm} + Km [a_{AQ} + (a - 1) t_A + (a - 1) \delta_R] + \delta_R + t_A + 2t_B (2m - 1) \]  
(4.48)

### 4.5.2 Total Interrogation Time Determination

The total interrogation time is given by (Figure 4.13)

\[ T^* = \sum_{i=1}^{M} t_{AQ} \]

where, \( t_{AQ} \) is given by (4.48). Substituting,

\[ T^* = \sum_{i=1}^{M} \left[ (Km - 1) t_{AQm} + Km [a_{AQ} + (a - 1) t_A + (a - 1) \delta_R] + \delta_R + t_A + 2t_B (2m - 1) \right] \]  
(4.49a)

applying \( \sum_{i=1}^{M} Km = N \); \( \sum_{i=1}^{M} m = \frac{M(M+1)}{2} \)

\[ T^* = [N-M] t_{AQm} + (aN-M+1) t_A + [N(a-1)+M] t_A + aN \delta_R + 2t_B (M^2) \]  
(4.49b)

Since the considerations about the two values of \( t_{AQ} \) explained in §4.4.3 also apply here, \( t_{AQm} \) is given by (4.40), and substituting:

\[ T^* = [N(a-1)+1] t_A + aN t_A + aN \delta_R + (N-M) \delta_R + 2t_B [M(M+1)+N] \]  
(4.49c)

but, \( t_B = \frac{M+1}{N} \) by definition of a block. Then:

\[ T^* = [N(a-1)+1] t_A + aN \delta_R + aN t_A + (N-M) \delta_R + 2N (M-1 + \frac{N}{M}) \]  
(4.50)
Figure 4.13. Determination of total interrogation time. Method V
For $M = 1$:

$$T_5 = \left[ N (a-1) + 1 \right] \Delta q + \alpha N \Delta R + \alpha N \Delta a + (N-1) \Delta H + 2 DN N$$

This equation shows that $T_5 = T_4$ for $M = 1$ as should be expected.

### 4.6. Sixth Method, Interrogation Of Blocks In Arbitrary Order, In Stream

This method is another means of providing total freedom in the order of interrogation*. This method uses the same block division already explained in Method IV but without the requirements for sorting the blocks by delay.

#### 4.6.1 Pause Between QDW's, Method VI

Since the performance of the system within a block is the same as in Methods IV and V, the values of $\Delta q_i$ and $\Delta a_m$ are readily determined by (4.13b) and (4.40) respectively.

To determine $\Delta q$, care must be taken to avoid overlapping of ADW's, even in the worst case of interrogation order. This worst case would occur when interrogating the last block before the first one. Then, $\Delta q$ is given by: (Figure 4.14)

$$\Delta q \geq \Delta q_m (m=M) - KM [\Delta a + (a-1) \Delta q_i + \Delta a_m] + \Delta a_m \quad (4.54)$$

*Method I is also in this category.
Figure 4.14. Determination of $t_{DQ}$. Method VI

$$t_1 = k_m [a_{DQ} + (a-1) t_{DQ_i}] + (k_m-1) t_{DQ_m} + t_{DQ}$$

$$t'_1 = t_{DQ_5} \quad (m = M)$$
where \( t_{\Delta 5} \) is given by (4.48) with \( m = M \). Hence,

\[
t_{\Delta 5} = k_m (a-1) t_a + k_m (a-1) \delta_a + a k_m t_a + (k_m-1) \delta_m + + (k_m + 2m - 2) 2 t_b
\]

substituting in (4.64) and applying (4.13b) and (4.40):

\[
t_{\Delta Q} \geq (k_m - 2) t_a - k_m t_a + (2m - 1) 2 t_b \tag{4.55}
\]

4.6.2 Total Interrogation Time, Method VI

Since the order of interrogation is arbitrary there is no way of making a graphical representation; however \( T_6 \) can be derived analytically.

The necessary time to send all the \( QD_5 \)'s measured at the head-end output terminals is given by:

\[
t_1 = \sum_{i=1}^{M} \left\{ k_m \left[ a t_a + (a-1) t_{\Delta Q_i} \right] + (k_m-1) t_{\Delta m} \right\} + (m-1) t_{\Delta Q} \tag{4.56}
\]

Additionally, time must be allowed for the last \( ADW \) (corresponding to the last \( QD_5 \) sent) to reach the head-end input terminals after the elapse of time \( t_1 \). This additional time is given as:

\[
t_2 = 2D_i + t_a - t_a \tag{4.57}
\]

where: \( D_i = \) delay to the last terminal interrogated

Thus, \( T_6 = t_1 + t_2 \), and applying (4.56) and (4.57):

\[
T_6 = \sum_{i=1}^{M} \left\{ k_m \left[ a t_a + (a-1) t_{\Delta Q_i} \right] + (k_m-1) t_{\Delta m} \right\} + (m-1) t_{\Delta Q} + t_a + - t_a + 2D_i
\]

The value \( 2D_1 \) can only be assumed, knowing that the upper bound is
2D_i = 2D_N + t_\ell.\quad \text{In order to make } T_6 \text{ minimum, (with respect to } D_i),

the lower bound value is assumed*. Therefore, applying (4.13), (4.40),

(4.55) and the assumed value of } D_i:

\[ T_6 = 2D_N \left[ \frac{(N+1)}{M} + 2(M-2) \right] + K_m (M-i) (t_A - t_A) + (N-M) t_R +
\]

\[ + \left[ a_N - (M-i) \right] t_A + \left[ N(a-1) + 1 \right] t_R + \left[ N(a-1) - (M-2) \right] t_A \]

where the relations, \( t_\ell = \frac{D_N}{M} \) and \( \sum_{m=1}^{M} K_m = N \) have been applied.

*This implies that the last terminal interrogated in any sequence is always one of the monitors at the head-end. This constraint is easily fulfilled by simply programming the system so that the last block interrogated is the closest one.
5. Conclusions.

5.1. Comparison of Total Interrogation Times

The total interrogation times have to be compared under equal conditions, which requires some assumptions.

The number of terminals in the system is assumed large \((N \gg 1)\) and the resolution time at the terminals \((\delta_R)\) is assumed always to be small compared to other parameters of the system \((i.e., t_A, t_a, D_N, D_{av})\). On the other hand, the resolution time at the head-end \((\delta_H)\), may include some processing, making \(\delta_H \gg \delta_R\); however, if there is little or no processing, \(\delta_H \approx \delta_R\). Thus \(\delta_H\) is either \(\gg \delta_R\) or \(\approx \delta_R\).

The values of the QDW length \((t_Q)\) and ADW length \((t_A)\) are always in the same range but their difference \(|t_Q - t_A|\) is greater than \(\delta_R\). Usually \(t_Q > t_A\), because the ADW does not include the ID code, but \(t_A\) may be \(> t_Q\), especially when the ADW does include the ID code. In either case, \((t_A + t_Q)\) is on the order of the maximum delay value in the system \((D_N)\).

Two extreme conditions are to be considered with respect to the terminal delay distribution function: concentration of subscribers close to the head-end \((D_{av} \ll t_A + t_a \lesssim D_N)\), and concentration of subscribers far from the head-end \((D_{av} \approx t_A + t_a \gtrsim D_N)\). A third condition corresponds to uniform distribution of subscribers \((D_{av} \approx \frac{D_N}{2})\).

\* \(\lesssim\): less than but close to.
Table 5.1a. - Comparison of Total interrogation times. Results.
<table>
<thead>
<tr>
<th></th>
<th>A2: ( t_A &gt; t_Q )</th>
<th>B1: ( S_H \approx S_R )</th>
<th>B2: ( S_H &gt;&gt; S_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1: ( D_a \approx D_N )</td>
<td>( \frac{T_{12}}{T_{32}} \approx 2 )</td>
<td>( \frac{T_{12}}{T_{32}} \approx 2 )</td>
<td>( \frac{T_{12}}{T_{32}} \approx 1 )</td>
</tr>
<tr>
<td>C2: ( D_a &lt; D_N )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 2 )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 3 )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 1.5 )</td>
</tr>
<tr>
<td>C3: ( D_a \approx \frac{D_N}{2} )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 2 )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 3 )</td>
<td>( \frac{T_{12}}{T_{32}} &lt; 1.5 )</td>
</tr>
</tbody>
</table>

Table 5.1b.-Comparison of Total interrogation times. Results.
Therefore, any arbitrary distribution may be considered as a combination of these three cases.

In addition to these assumptions, the following considerations apply when comparing the various block-grouping interrogation methods: the number of blocks \( M \) is always much less than the number of terminals; however, at the same time \( M \) is \( \gg 1 \) so that the number of terminals in any block \( K_m \) is much less than \( N \).

Applying these assumptions, the range of variation of the ratios of the total interrogation times can be calculated* for the different conditions given. Basically, the preceding methods fall into two classes; one in which terminals are arranged into blocks having a common delay range; and the other in which blocking is not used. To compare both classes, the fastest methods of interrogation for each class already determined in Chapter 4 are used (i.e. Method II and Method IV).

The results are shown in Tables 5.1a and 5.1b, where the subindex of the parameter \( T \) indicates the equations used for each condition, and the right hand limit of the range (if there is such) corresponds to the maximum redundancy considered \( (a = 3) \).

These six methods of interrogation presented (Chapter IV) do not pretend to exhaust the possibilities; however, they represent the

*See Appendix.
basic principles such that other methods would be variations and combinations of these six.

Choosing the method for a system depends upon the particulars of each system. Usually the task is to reach the lowest cost possible for the speed of interrogation required in the particular application.

The cost in equipment and maintenance increases with the timing control needed at the head-end and with the need for sorting the terminals by delay. On this premise, Methods I and III are the less expensive; followed by Methods VI and V; with Methods IV and II as the most expensive.

Taking Method I as a reference, the relative speed of the other methods can be represented as a function of the redundancy (a).

Figures 5.1a, b, c and d, represent these variations for the different conditions; the data has been taken from Tables 5.1a and b, so that it is a qualitative representation under the indicated conditions.

From Figure 5.1a, where conditions A1 (tQ>tA) and B1 (no processing included in δw) apply, Method III offers no advantage over Method I for the no redundancy condition (a = 1), as should be expected; therefore, if a method faster than I is needed, Method II is the preferred alternative. However, if redundancy is required (a = 3), Method III represents an alternative under condition C1 (Daw=DN)
Figure 5.1.- Comparison of Total interrogation times. Results.
which should be considered when increasing the speed is necessary.

Under B2 (processing included in $\mathcal{H}$), the gain in speed with Method II decreases so as to make Method III the proper choice under condition C1 ($a = 3$). Method III also represents an alternative under C3 (uniform distribution). (Figure 5.1b)

Under A2 ($t_A t_Q$) is satisfied, with no processing included in $\mathcal{H}$ (Bl), the results under conditions Al and Bl are similar, with the difference that Method III (used with redundancy) represents an alternative not only for C1 ($D_A DN$) but also for C3 (uniform distribution).

As processing time is included in $\mathcal{H}$, the gain in speed with Method II is decreased and Method III becomes an alternative to be considered for increasing speed in systems with redundancy.

Although Method III was defined as a particularization of Method I, to increase the speed of interrogation (for $a > 1$) with little sacrifice in cost, the results show that in many cases the gain in speed is quite small or even negative. However, it may be inferred from the results that Method III provides better relative speed when the maximum delay in the system is much larger than other parameters (i.e. $DN \gg t_Q$) and the terminals are concentrated at the far end of the system ($D_A DN$); especially if the head-end processes each ADW as received ($\Delta u \gg \delta u$).
Method II is, indeed, the fastest method; but, since its cost is also much higher than Method I and III, one must consider carefully the relative importance of speed. Particularly when the terminals are concentrated closed to the head-end (\(D_{av}\ll DN\)) and/or each ADW is processed as received (\(\delta w \gg \delta a\)), the increase in interrogation speed is lower and it could be disadvantageous in the speed-cost trade-off to apply Method II.

The relative interrogation speed variation of the methods under the blocking procedure is not shown in Figures 5.1, because it is known that their interrogation speed is less than, but very close to Method II \(II \succ IV \simeq V \succ VI\). Since all these methods (blocking procedures) are less expensive than Method II, it can be concluded that under the given conditions, Methods IV, V or VI are better choices whenever Method II is the potential solution. One exception to the former statement may occur when the block width \(t_B\) necessary to satisfy \((4.40)\) under \(Al\) \((tQ>tA)\) is so large (this implies \(\delta w \approx \delta a, t_a \gg t_A\)) that for short systems the assumptions \(M \gg l\) and \(K_m \ll N\) are no longer valid. In such a case, the decrease in speed is larger than that shown in Tables 5.1, and Method II is an alternative to consider.
REFERENCES


(8) Reference Data, Bidirectional Amplifier 2-300, CORAL, North Bergen, New Jersey, U.S.A.


APPENDIX

A.l. **Comparison of Total Interrogation Times**

General Assumptions:

(a) The number of terminals is very large, \( N \gg 1 \)

(b) The values of \( t_Q \) and \( t_A \) are in the same range, but \[ |(t_Q - t_A)| > \delta_R. \] Also their sum is on the order of the maximum delay of the system: \( (t_Q + t_A) \approx \delta_{DN} \). It may be, either \( A_1: t_Q > t_A \) or \( A_2: t_A > t_Q \)

(c) The resolution time at the head-end (\( \delta_H \)) is either approximately equal to \( \delta_R \) or much greater than \( \delta_R \).

\[ \delta_H = \delta_R \quad \text{or} \quad \delta_H > \delta_R \]

(d) The resolution time at the terminals is always small compared to other parameters of the system. (\( \delta_R \) small)

(e) The distribution of terminals along the system is considered for three extrema:

1. Concentration of subscribers around the maximum delay of the system. \( \delta_{AV} \approx t_A + t_Q \approx DN \)

2. Concentration of subscribers close to the head-end. \( \delta_{AV} < t_A + t_Q \approx DN \)
C3. Uniform distribution of subscribers. Dav ≈ \frac{t_a + tA}{2} ≈ \frac{DN}{2}

(f) The number of blocks \(M\) is much less than the number of terminals \(N\), and the number of terminals in any block \(K_m\) is much less than \(N\). Also (4.40) is always satisfied: \(M \ll N; K_m \ll N\).

A.1.1. Conditions Al, Bl.

Al. \(t_a > tA\) ; Bl. \(\delta_R \approx \delta_R\).

1.1.1 Methods I and III. Under Al, Bl, 2 Dj (4.8b) becomes negative, which implies that:

\[ D_i > D_j \]

and \(T_1\) is given by (4.7). Since the value of \(\delta_R \approx \delta_R\) is assumed small, then:

\[ D_i > \frac{\delta_R}{2} \]

so that \(T_3\) is given by (4.33). Therefore, taking the ratio of \(T_1\) to \(T_3\):

\[
\frac{T_1}{T_3} = \frac{eN(t_a + tA + \delta R) + 2anDav}{eN(t_a + tA + \delta R) + 2nDav}
\]

\[
\frac{T_1}{T_3} = 1 + \frac{2(a-1)Dav}{a(t_a + tA + \delta R) + 2Dav}
\]

(1)

applying Cl and d:

\[
\frac{T_1}{T_3} \approx 1 + \frac{2(a-1)}{(a+2)}
\]
Thus, \( 1 \leq \frac{T_1}{T_3} < 2 \) as \( a \) varies from 1 to 3.

Applying C2, \( \frac{T_1}{T_3} \geq 1 \) for \( 1 \leq a \leq 3 \)

and applying C3 and (d) in (1)

\[
\frac{T_1}{T_3} \approx 1 + \frac{(a-1)(t_a-t_a)}{(a+1)(t_a-t_a)} = 1 + \frac{a-1}{a+1}
\]

Thus, \( \frac{T_1}{T_3} \approx 1 \) as \( a \) varies from 1 to 3.

1.1.2 Methods I and II - \( T_1 \) is still given by (4.7). Under Al and Bl, (4.17) is satisfied, so that \( T_2 = T_{21} \) (4.23). Therefore,

\[
\frac{T_1}{T_{21}} = \frac{a_N(t_a+t_a+5r)+2aN\delta v}{aNt_a + \left[ N(n-1)+1 \right] t_A + a_N5r + 2DN}
\]

dividing by a \( N \),

\[
\frac{T_1}{T_{21}} \approx \frac{(t_a+t_a+5r)+2\delta v}{(t_a+t_a+5r)-t_A/a}
\]

where \( 2DN/aN \) and \( tA/an \) have been neglected. Applying Cl and d,

\[
\frac{T_1}{T_{21}} \approx 3(t_a+t_a) \quad \text{or} \quad 6 > \frac{T_1}{T_{21}} > \frac{4}{3} \quad \text{for} \quad 1 \leq a \leq 3
\]

Applying C2 and (d) in (2), \( 2 > \frac{T_1}{T_{21}} > 2 \) or \( \frac{T_1}{T_{21}} \approx 2 \) for \( 1 \leq a \leq 3 \).

Finally, for C3 and d in (2):

\[
\frac{T_1}{T_{21}} \approx \frac{2(t_a+t_a)}{t_A+t_a-t_A/a} \quad \text{or} \quad 4 > \frac{T_1}{T_{21}} > \frac{4}{3} \quad \text{for} \quad 1 \leq a \leq 3
\]

1.1.3 Methods II and III - Since (4.17) is satisfied (Al, Bl), \( T_2 = T_{21} \) (4.23) and \( T_3 = T_{31} \) (4.35). Therefore:
\[ \frac{T_{31}}{T_{21}} = \frac{aN(ta + 3a) + 3H + (aN + 1)ta - k^2 (ta + 2 D aV3) + 2 N D aV3}{aNta + an \Delta ta - (N-1)ta + an \delta R + 2 D \eta aN} \]

dividing by \( aN \) and neglecting \( \delta H/aN, \tau A/aN \) and \( 2 \delta N/aN; \)

\[ \frac{T_{31}}{T_{21}} \approx \frac{ta + 3a + ta + (1 - \frac{k^2}{aN})2 D aV3 - \frac{k^2}{aN} \tau A}{ta + 3a + ta - ta/a} \]

Under Cl, \( K_3 \ll N \) and \( D aV_3 \rightarrow \) Then:

\[ \frac{T_{31}}{T_{21}} \approx \frac{ta + 3a + ta + 2 D aV3/a}{ta + 3a + ta - ta/a} \]

Hence \( 6 \geq \frac{T_{31}}{T_{21}} > 1 \) for \( 1 \leq a \leq 3 \).

For condition C2, \( K_3 \) may be large, but from Cl, \( \delta H/2 \) is very small, and \( K_3 \) may still be assumed \( \ll N \). On the other hand, \( D aV_3 > D aV \), so that one may assume \( D aV_3 \approx taQ \). Then (3) becomes:

\[ \frac{T_{31}}{T_{21}} \approx \frac{ta + 3a + ta + taQ/a}{ta + 3a + ta - ta/a} \] ; or \( 6 \geq \frac{T_{31}}{T_{21}} > 1 \) for \( 1 \leq a \leq 3 \)

For C3, \( D aV_3 \cong D aV \), so that the result is approximately the same as under Cl: \( 6 \geq \frac{T_{31}}{T_{21}} > 1 \) for \( 1 \leq a \leq 3 \)

1.1.4 Methods IV and V - Since condition (f) applies, the ratio of \( T_5 \) to \( T_4 \) becomes: (4.50) (4.44)

\[ \frac{T_5}{T_4} = \frac{[N(a-1)+1]ta + an \delta R + an \tau A + (N-M) \delta H + 2 D N [M-1 + \frac{N}{M}]}{[N(a-1)+1]ta + an \delta R + an \tau A + (N-M) \delta H + 2 D N [1 + \frac{N-1}{M}]} \]

dividing by \( aN; \)

\[ \frac{T_5}{T_4} \approx \frac{ta + 3a + ta + \frac{1}{a} (ta + 3H) + (\frac{M}{aN} + \frac{1}{aM})2 D N}{ta + 3a + ta + \frac{1}{a} (ta + 3H) + (\frac{M}{aN} + \frac{1}{aM})2 D N} \]

Then, \( \frac{T_5}{T_4} \cong 1 \), independently of \( 1 \leq a \leq 3 \) and other parameters of the
system (i.e. A1, A2, B1, B2, C1, C2, C3).

1.1.5 Methods IV and VI

From (4.44) and (4.59) the ratio becomes:

\[
\frac{T_e}{T_f} = \frac{[N(a-1) - (M-2) + KM(M-1)] ta + [N(a-1) + 1] \delta r + [aN - (M-1) - KM(M-1)] ta + (N-M) \delta h +}{[N(a-1) + 1] ta + aN \delta r + aN ta + (N-1) \delta h +} \\
\frac{+ 2DN \left[ \frac{N+1}{M} + 2(M-2) \right]}{+ 2DN \left[ 1 + \frac{N-1}{M} \right]}
\]

dividing by aN, and taking KM \cdot M = N (Cl)

\[
\frac{T_e}{T_f} \approx \frac{ta + \delta r + ta - \frac{1}{a} (ta - \delta h) + 2DN \frac{1}{aN}}{ta + \delta r + ta + \delta h/a + 2DN/aM} \quad (5)
\]

Thus, \( \frac{T_e}{T_f} \approx 1 \) for the range of 1 ≤ a ≤ 3 and independently of the other conditions, except (f).

1.1.6 Methods V and VI

The values for total interrogation time are given by (4.50) and (4.59), thus:

\[
\frac{T_e}{T_s} = \frac{[N(a-1) + (KM-1)(M-1) + 1] ta + [N(a-1) + 1] \delta r + [aN - (KM+1)(M-1)] ta + (N-M) \delta h +}{[N(a-1) + 1] ta + aN \delta r + aN ta + (N-M) \delta h + 2DN \left[ M-1+ \frac{N}{M} \right]} \\
\frac{+ 2DN \left[ \frac{N+1}{M} + 2(M-2) \right]}{+ 2DN \left[ 1 + \frac{N-1}{M} \right]}
\]

dividing by aN with KM \cdot M = N:

\[
\frac{T_e}{T_s} \approx \frac{ta + \delta r + ta - \frac{1}{a} (ta - \delta h) + 2DN \frac{1}{aN}}{ta + \delta r + ta + \delta h/a + 2DN \frac{1}{aNM}} \quad (6)
\]
Hence, \( \frac{T_4}{T_2} < 1 \) for the range of \( 1 \leq a \leq 3 \) and independent of the other conditions except (f).

1.1.7 Both Procedures - Methods II and IV

\( T_4 \) is given by (4.44) in any condition (but \( f \)); however, the equation for \( T_2 \) depends on the other parameters of the system.

For conditions Al and Bl, (4.17) is satisfied, so that

\[
T_2 = T_{21} \quad (4.23) \quad \text{and:}
\]

\[
\frac{T_4}{T_{21}} \sim \frac{\frac{tA + sR + tA - (tA + sH)/a + 2DN/aN}{tA + sR + tA - tA/a}}
\]

therefore, \( T_4/T_{21} < 1 \) regardless of \( C_1, C_2, C_3 \), for any range of \( a \).

A.1.2 Conditions Al, B2

Al. \( tA > tA \) \quad B2. \( sH > sR \)

1.2.1 Methods I and III - From B2, (4.19) holds and 2 \( D_j \) is a significant parameter; thus \( T_1 = T_{12} \) (4.12a) and \( T_3 = T_{32} \) (4.36).

Then,

\[
\frac{T_{12}}{T_{32}} = \frac{(an+1)(tA+sR)+aNtA + AN(2Dav1) - sH + 2D_i - aK_1(sR - sh + tA + 2Dav1)}{(an+1)(tA+sR)+ANtA + N(2Dav1) - K_3(sR - sh + tA + 2Dav3)}
\]
Substituting $2D_j = t_A - t_Q + 3H$ and dividing by $aN$: \[ \frac{T_{12}}{T_{32}} \approx \frac{t_A + 3R + t_A + 2Dav_1 - \frac{K_1}{N} (2Dav_1 + t_A + 3R - 3H)}{t_A + 3R + t_A + 2Dav_3 - \frac{K_3}{aN} (2Dav_3 + t_A + 3R - 3H)} \] (8)

For C1, $K_1 < K_3 << N$ and $Dav_1 \approx Dav_3 \approx Dav \approx (t_A + t_Q)$. Hence, \[ 1^2 \frac{T_{12}}{T_{32}} < 3 \quad \text{for} \quad 1 \leq a \leq 3 \]

If C2 holds, $K_2 \approx K_3 \approx N$, so that:

\[ 1^2 \frac{T_{12}}{T_{32}} \approx 1 \]

finally, for the uniform distribution (C3), $Dav \approx \frac{1}{2} DN$, \[ K_1 \approx K_3 \approx \frac{N}{2} \quad \text{Therefore (8) becomes:} \]
\[ \frac{T_{12}}{T_{32}} \approx \frac{t_A + 3R + t_A + \frac{1}{2} (t_A + t_A)}{t_A + 3R + t_A + \frac{1}{2a} (t_A + t_A)} \approx \frac{3/2}{1 + 1/2a} \]
and, \[ 1^2 \frac{T_{12}/T_{32}}{< 1.5} \]

1.2.2 Methods I and II - $T_1 = T_{12} (4.12b)$ and $T_2 = T_{22} (4.24)$, so that the ratio becomes:
\[ \frac{T_{12}}{T_{22}} = \frac{(aN+1)(t_A + 3R) + aN t_A + aN (2Dav_1) - 3H + 2Dj - aK_1 (3R - 3H + t_A + 3Dav)}{[N(a-1)+1] t_A + aN t_A + 3R [N(a-1)+1] + 3H (N-1) + 2DN} \]

substituting $2D_j$ and dividing by $aN$:
\[ \frac{T_{12}}{T_{22}} \approx \frac{t_A + 3R + t_A + (2 - \frac{K_1}{N}) 2Dav_1 - \frac{K_1}{N} (3R - 3H + t_A)}{t_A + 3R + t_A - t_Q/a + 3H/a} \]
From (B2) and \(d\), the factor \((\delta_a - \delta_w + ta)\approx 0\); also \((\delta_w - \frac{ta}{a})\approx 0\).

Then, for Cl, \(K_1 < N\) and \(Dav_1 \approx Dav\), and applying (B2) and \(d\):

\[
\frac{T_{12}}{T_{22}} \approx \frac{3(ta + ta)}{(ta + ta)} = 3
\]

which implies that \(\frac{T_{12}}{T_{22}} \approx 3\) regardless of \(a\).

If C2 holds, \(K_1 \approx N, Dav_1 > Dav\) and then \(\frac{T_{12}}{T_{22}} \approx 2\);

and for (C3), \(Dav \approx \frac{1}{2} DN\) and from (B2), \(K_1 \approx \frac{N}{4}\). Hence, \(\frac{T_{12}}{T_{22}} \approx 2\).

1.2.3 **Methods II and III** - For (B2), (4.19) holds and \(T_2 = T_{22}(4.24)\),

\[T_3 = T_{32}(4.36),\] Hence,

\[
\frac{T_{32}}{T_{22}} = \frac{(an+1)ta + an^2a + (an+1)5r + 2NDav_3 - K_3 (5r - \delta_h + \delta q + 2Dav_3)}{[N(a-1)+1] ta + an^2a + 5r [N(a-1)+1] + \delta h (N-1)+2DN}
\]

dividing by \(aN\) and applying (B2) and \(d\):

\[
\frac{T_{32}}{T_{22}} \approx \frac{ta + ta + (\frac{2}{a} - \frac{K_3}{aN}) Dav_3}{ta + ta}
\]

If Cl applies; \(K_3 \ll N\) and \(Dav_3 \approx Dav\). Then:

\[
\frac{T_{32}}{T_{22}} \approx 1 + \frac{2}{a} \quad \text{or} \quad 3 \approx \frac{T_{32}}{T_{22}} \leq 2 \quad \text{for} \quad 1 \leq a \leq 3
\]

For C2, \(K_3 \approx N, Dav_3 > Dav\) so that:

\[
2 < \frac{T_{32}}{T_{22}} \leq 1 \quad \text{for} \quad 1 \leq a \leq 3
\]

and for C3, \(K_3 \approx \frac{N}{4}\) and \(Dav_3 > Dav\), thus (10) becomes:

\[
\frac{T_{32}}{T_{22}} \approx 1 + \frac{7}{4a} \quad \text{or} \quad 3 \approx \frac{T_{32}}{T_{22}} \leq 1.5
\]

1.2.4 **Both Procedures - Methods II and IV** - For condition (B2), (4.19)
is satisfied, so \( T_2 = T_{22} \) (4.24). Therefore:

\[
\frac{T_q}{T_{22}} = \frac{[N(a-1)+1]ta + \alpha ta + 5R\alpha N + \delta H(N-1) + 2DN [1 + \frac{N-1}{\alpha M}] - 5R[aN + 5R(N-1) + 2DN]}{[N(a-1)+1]ta + \alpha ta + 5R[aN + 1] + \delta H(N-1) + 2DN}
\]

Dividing by \( aN \) and neglecting the proper terms:

\[
\frac{T_q}{T_{22}} \approx \frac{ta + \delta R + (\delta H - ta)/\alpha + 2DN/\alpha M}{ta + \delta R + (\delta H - ta)/\alpha} \approx 1 + \frac{2}{\alpha M} \quad (11)
\]

Since \( M > 1 \), \( \frac{T_q}{T_{22}} \ll 1 \) regardless of \( C_1, C_2 \) and \( C_3 \).

### 1.3 Conditions \( A_2, B_1 \)

#### 1.3.1 Methods I and III

Under \( A_2 \), (4.19) always hold and \( 2D_j \) is a significant parameter; hence, \( T_1 = T_{12} \) (4.12a) and \( T_3 = T_{32} \) (4.37), so that the ratio is given by (8):

\[
\frac{T_{12}}{T_{32}} \approx \frac{ta + \delta R + ta + (2 - \frac{2K_1}{N})Dav_1 - \frac{K_1}{N}(ta + \delta R - \delta H)}{ta + \delta R + ta + (2 - \frac{2K_3}{N})Dav_3 - \frac{K_3}{N}(ta + \delta R - \delta H)}
\]

For \( B_1 \), \( K_3 \ll N \) and \( Dav_3 \approx Dav \), thus:

\[
\frac{T_{12}}{T_{32}} \approx \frac{ta + \delta R + ta + (2 - \frac{2K_1}{N})Dav_1 - \frac{K_1}{N}(ta + \delta R - \delta H)}{(1 + \frac{2}{\alpha})(ta + ta)} \quad (12)
\]

Now under \( C_1 \), \( K_1 \ll N \) and \( Dav_1 \approx Dav \), then,

\[
\frac{T_{12}}{T_{32}} \approx \frac{3}{1 + 2/a}, \quad \text{or} \quad 1 \approx \frac{T_{12}}{T_{32}} \ll 2 \quad \text{as} \quad 1 \leq a \leq 3 \quad \text{Considering}
\]

\( C_2 \), \( K_1 \approx N \) so \( \frac{T_{12}}{T_{32}} \approx \frac{1.5}{1 + 2/a} \), or \( \frac{1}{2} \ll \frac{T_{12}}{T_{32}} \ll 1 \) Finally, if \( C_3 \) holds, \( K_1 \) may still be considered \( \ll N \), but the numerator of
the ratio decreases with respect to its value under C2; hence,

\[ 1 < \frac{T_{12}}{T_{32}} < 2 \quad \text{for} \quad 1 \leq a \leq 3 \]

1.3.2 Methods I and II - Since (A2) is satisfy, (4.19) holds and 

\[ \frac{T_{1}}{T_{2}} \] 

is given by (9) as:

\[ \frac{T_{12}}{T_{12}} \approx \frac{ta + tA + (2 - \frac{K}{N})DaV - K \frac{tA}{a}}{tA + ta - tA/a} \]

where the term \( \delta_w \) and \( \delta_k \) have been neglected \((B1) (d)\). For (C1), 

\[ K_1 < \frac{N}{D_{a1}} \Rightarrow \frac{T_{12}}{T_{12}} \approx 3.5 \]

If (C2) applies, \( K_1 \approx N \) and 

\[ 3 \frac{T_{12}}{T_{12}} < 2 \]

Finally, for uniform distribution (C3),

the value of the ratio range lies somewhere in between the ranges

corresponding to the conditions C1 and C2. Therefore, 

\[ 4 \frac{T_{12}}{T_{12}} > 3 \]

1.3.3 Methods II and III - Since (4.19) holds, \( T_2 = T_{22} \) and \( T_3 = T_{32} \), 

thus,

\[ \frac{T_{32}}{T_{12}} \approx \frac{(a + 1)ta + aNTa + (a + 1)\delta k + 2N DaV - K_2 (\delta k - \delta k + tA + 2 DaV)}{[N(a - 1) + 1]ta + aNTa + \delta k [N(a - 1) + 1] + \delta k (N - 1) + 2 DN} \]

dividing by \( aN \) and applying \((B1) \) and \( (d)\); \( K_3 \ll \frac{N}{D_{a1}}, DaV_3 \approx DaV \)

\[ \frac{T_{32}}{T_{12}} \approx \frac{ta + ta + 2 DaV}{ta + ta - ta/a} \]

For C1, 

\[ 6 \frac{T_{32}}{T_{12}} > 2 \quad \text{as} \quad 1 \leq a \leq 3 \]

For C2, 

\[ 2 \frac{T_{32}}{T_{12}} > 1 \quad \text{as} \quad 1 \leq a \leq 3 \]

For C3, 

\[ 4 \frac{T_{32}}{T_{12}} > 2.5 \quad \text{as} \quad 1 \leq a \leq 3 \]

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1.3.4 Both Procedures Methods II and IV - Since (4.19) holds, the ratio is given by (11), and the range remains the same as under conditions Al and B2; therefore from § A.1.2.4:

\[ \frac{T_L}{T_{zz}} \geq 1 \]
regardless of Cl, C2 and C3.

1.4. Conditions A2, B2

A2. \( t_A > t_Q \)
B2. \( \delta_R >> \delta_a \)

1.4.1 Methods I and II - From § A.1.2.1:

\[ 1 \leq \frac{T_L}{T_{zz}} < 3 \]

C1

\[ \frac{T_L}{T_{zz}} \approx 1 \]

C2

\[ 1 \leq \frac{T_L}{T_{zz}} < 1.5 \]

C3

1.4.2 Methods I and II - From § A.1.2.2:

\[ \frac{T_L}{T_{zz}} \approx 3 \]

C1

\[ \frac{T_L}{T_{zz}} \geq 2 \]

C2

\[ \frac{T_L}{T_{zz}} \geq 2 \]

C3

1.4.3 Methods II and III - From § A.1.2.3

\[ 3 \approx \frac{T_{zz}}{T_{zz}} \geq 2 \]

C1.
\[ 2 < \frac{T_{32}}{T_{22}} \leq 1 \quad \text{C2} \]

\[ 3 \approx \frac{T_{32}}{T_{22}} \leq 1.5 \quad \text{C3} \]

1.4.4 Both Procedures Methods II and IV - From A.1.2.4

\[ \frac{T_4}{T_{22}} \leq 1 \]
VITAE

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