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Properties of subscribers' lines and their influence on telephone transmission performance

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Proefschrift

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Contents

Preface

The contents of this treatise form part of studies in the field of telephone transmission planning carried out by the author in the Dr. Neher Laboratories of the Netherlands Postal and Telecommunications Services (PTT). The author is grateful for the opportunity given to him for publishing this work.
Appreciation is expressed to many colleagues and co-workers in the Dr. Neher Laboratories and in other departments of the PTT. They contributed to the completion of this work by means of helpful discussions, by making information available, by carrying out measurements and numerical calculations or by preparing the illustrations. Thanks are also due to the Foreign Languages Branch for correcting the English text.
This treatise is divided into five chapters, each of which contains a number of sections, which are sometimes further subdivided. At the end of each chapter a list of references is included.
The views expressed and the conclusions drawn are those of the author; they do not necessarily reflect the opinion of the Netherlands PTT.

C. Bakker

1 Introduction

1.1 *General background*

About hundred years after its invention the telephone has become an indispensable means of communication in present economic and social life. And its importance is still growing, owing to the still increasing number of subscribers all over the world. In the Netherlands the number of subscribers reached the level of three million recently, on a total population of about 13.6 million. With such a subscriber density the Netherlands are internationally in the forefront, although in many countries of the Western World figures are similar, and in some cases even about twice as much.

Moreover, thanks to technical developments, longer and longer distances could be covered by telephone. At present only a good half of all the calls made in the Dutch public telephone system are local calls, while the proportion of trunk calls is increasing [1]. International calls amount to some per cent, and the growth rate of this category is roughly three times that of the total telephone traffic. Especially stimulated by the introduction of advanced means of transmission, such as transatlantic telephone cables and synchronous-orbit communication satellites, there is even a growing familiarity with intercontinental calling.

Nowadays a world-wide and complex system of transmission and switching equipment is at the disposal of the telephone subscriber. And in many cases the system is under his direct control; a simple rotary dial, or in the most modern systems a small keyset, is the tool to effect this.

A sufficient transmission quality in such a complex system requires a careful designing of all parts of the system and a strict observance of planning and maintenance rules for the system as a whole. In spite of the large variety of transmission methods available in the world-wide telephone network–ranging from baseband transmission on a pair of conductors in a multipair cable to frequency or time division multiplex transmission in a highly sophisticated multi-channel system–the basic form of the transmission path involved in a long-distance call can be represented by the rather simple diagram depicted in Figure 1.1a.

In this diagram the long-distance part of the connection consists of a four-wire*

* Many more or less generally known terms are in use in the field of telephone transmission. As a help to the reader a glossary containing definitions of a number of terms used in this treatise, has been annexed. In so far as possible, definitions have been taken from the '*List of definitions of essential telecommunication terms*', published by the International Telecommunication Union [2].

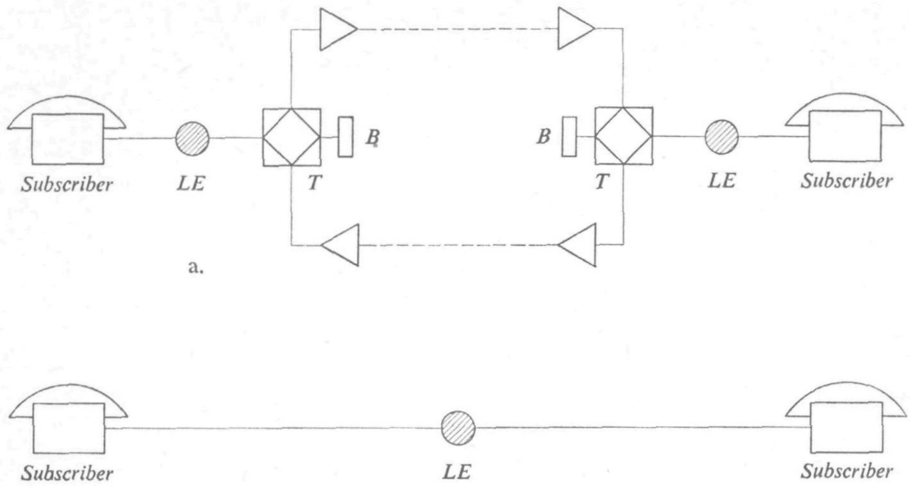


Figure 1.1 b.

transmission path, provided with repeaters for each direction of transmission. The telephone sets at both ends are connected to the four-wire path by means of two-wire cable circuits. The transition from two-wire to four-wire (and vice versa) is achieved in the'four-wire terminating sets' *T*, usually containing hybrid transformers and a balancing network *B*. These terminating sets provide transmission between the two-wire circuits and the 'go' and 'return' channel of the four-wire path, but at the same time decouple as much as possible both directions of transmission of the four-wire transmission path.

In general the four-wire part of a connection may consist of a number of four-wire circuits in tandem, interconnected (on a four-wire basis) in telephone switching centres. Also the two-wire parts can contain one or more (two-wire) switching centres. In order to emphasize the basic form of a connection most of these centres have been omitted in the diagram of Figure 1.1a, with the exception of the local exchange (*LE*), to which the subscriber is connected direct by means of the 'subscriber's line'. Many calls can be established via a connection of much simpler composition. In the case of local calls between two subscribers connected to the same local exchange, the diagram will be reduced to Figure 1.1b. The two local exchanges in Figure 1.1a. will overlap and the complete connection only contains two telephone sets with subscribers' lines, interconnected in the local exchange.

With business calls a private branch exchange (PBX) will often be found in the connection between the telephone set and the local exchange. Usually the extension line between set and PBX will be very short. Extension-to-extension calls (inside the same PBX-network) can also be indicated by Figure 1.1b; then the 'subscribers' lines' are normally very short.

In principle, a local exchange serves all subscribers in a certain area surrounding the exchange building: the 'exchange area'. Therefore, in practice, the length of subscribers' lines may vary from some metres to several kilometres, depending on the shape and dimensions of the exchange area, configuration of the cable plant, etc. Because of the fact that for economic reasons the diameter of conductors used for subscribers' lines should be small, this variation in length will cause a substantial spread in attenuation of speech signals on subscribers' lines.

In the four-wire part of a connection, attenuation can be compensated for by amplifiers, which also can be given some extra gain for the purpose of cancelling (partly) the attenuation of the two-wire parts.* The possibilities of providing surplus-gain are very restricted, because of imperfect balancing conditions at the terminating sets, which are in practice unavoidable. The 'balance return loss', i.e. the suppression of transmission across the terminating set, depends on the degree of mismatch between the impedance of the balancing network and the impedance of the two-wire circuit as seen at the two-wire side of the terminating set. The latter impedance is largely influenced by the characteristics of the subscriber's line and the telephone set. Usually balancing conditions are such that transmission from one side of the four-wire circuit to the other side is only partly suppressed. This means that if the gain in the four-wire chain is increased, there is the risk that in the loop, formed by the 'go' and 'return' path and the two terminating sets, the result at some frequency will be a positive gain and such phase conditions that instability will occur. This becomes perceptible as 'singing'. In these considerations due account should be taken of all unavoidable variations of each of the four-wire circuits in the complete chain.

But even if the loop-gain is negative for all frequencies, the call can be seriously affected by the following: signals from the 'go' path will (more or less attenuated) leak across the terminating set at the far end. As a result of propagation time these signals will, with some delay, be received as a reflected signal by the talking subscriber ('talker echo'). The longer the delay, the more troublesome this echo will be. With international connections propagation time can be considerable, and rather high values of loss in the echo-path are required to make the echo tolerable.

Although the basic forms of a telephone connection could be represented by rather simple diagrams, Figure 1.1 does not reflect the multiplicity of factors which can influence the quality of a telephone conversation. The primary task for a telephone connection is to enable two customers to communicate in a satisfactory way. So, ultimately the planning of a telephone network should be based on subscribers' opinions. With this criterion an important extra source of variations is introduced. These variations are on the one hand due to differences among subscribers in such irrational

* In principle attenuation can also be compensated for in the two-wire parts by means of 'two-wire repeaters' or by negative impedance repeaters (negistors). In both cases severe stability problems can arise [3, 4]. Therefore it has become common practice to use four-wire transmission and switching for repeatered circuits, as was assumed in Figure 1.1a.

aspects as judgement and appreciation, but there are on the other hand differences of a more physical nature, such as level and frequency spectrum of speech, threshold of audibility, etc. Even the shape of ears and mouths and the dimensions of heads in relation to the telephone handset play their part. The resulting effect is that for a given, well-defined connection (from handset to handset) opinions about the transmission quality may vary considerably amongst users.

Several methods for assessing and rating speech transmission quality are known [5], all applying a statistical approach. Such an approach is even more needed for the assessment of speech transmission performance for the ensemble of possible connections in a telephone network. There even more variables are involved. Firstly there are variations resulting from routing. As indicated in Figure 1.1, a telephone connection can vary from a rather simple one inside an exchange area to a very complex intercontinental one. Depending on the position of the local exchanges in the hierarchy of the telephone network the composition of the two-wire ends can be more or less complex. The four-wire chain can contain from one up to about twelve circuits, switched in tandem to form (temporarily) a complete connection, in which each circuit has a nominal loss, amounting to 0.5 dB for international circuits [6]. And last but not least, the attenuation and impedance of the subscribers' lines at both ends can show considerably different values for different calls.

Moreover, practical values of loss of separate parts of the connection can deviate from their nominal value. This applies to the characteristics of telephone sets, which are usually subject to considerable tolerances. More or less severe deviations from the nominal characteristics will also occur at each of the circuits included in the four-wire chain, because in practice each circuit is lined up individually. So deviations accumulate if circuits are switched in tandem. These deviations in the four-wire chain are also particularly important for the stability and echo problems described before.

Apart from loss, there are several other factors that can influence telephone conversations, e.g. noise, crosstalk and other disturbing signals, linear and non-linear distortion, frequency shift, echo signals, etc. In Figure 1.2 we tried to give an impression (not an exhaustive description) of a number of variables and impairments which can be involved in a telephone conversation.

In a modern telephone network loss is the most important of all these factors. But obviously, the necessity to restrict the overall loss of a connection can be in conflict with requirements concerning echo effect and circuit stability, because lower loss in the four-wire chain means greater problems with regard to echo and stability.

The foregoing shows that long-distance transmission planning is a complex matter. It will be clear that international consultation and co-ordination is indispensable in order to lay down rules for the interconnection of national telephone networks. In fact an international transmission plan is needed.

The international co-ordination of telecommunication is consigned to the International Telecommunication Union (ITU), a specialized agency of the United Nations. Within

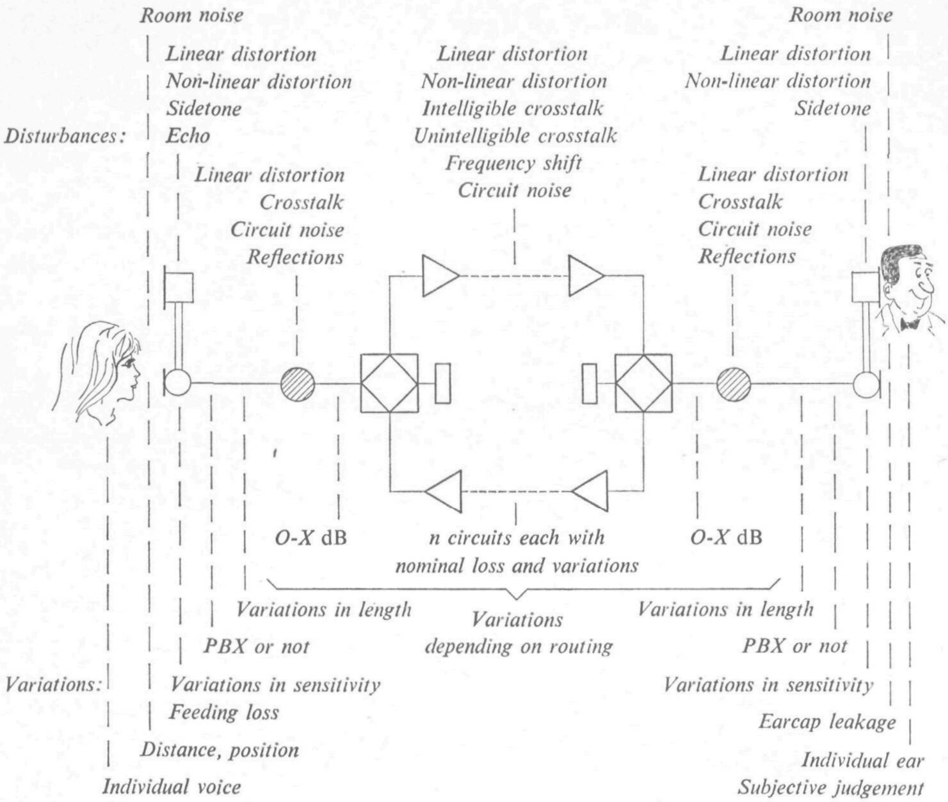


Figure 1.2

ITU the CCITT (Comité Consultatif International Télégraphique et Téléphonique = International Telegraph and Telephone Consultative Committee) studies questions and issues recommendations in the field of telegraphy and telephony. The work entrusted to the CCITT is to a large extent performed by Study Groups; the programs of Study Group XII and Study Group XVI particularly relate to the problems which are discussed in this treatise. Study Group XII deals with telephone transmission quality, local lines and telephone sets. Study Group XVI deals more generally with telephone circuits and complete connections, formulating recommendations concerning characteristics and planning rules [7]. Recommendations drafted by the Study Groups are discussed and ratified in the Plenary Assembly of the CCITT, which normally meets every four years. After each Plenary Assembly all valid recommendations are published as a 'Book' consisting of a number of volumes. The most recent version, issued after the Plenary Assembly at Geneva in 1972, is the '*Green Book*'; a different colour is used for each study period. Several times reference will be made in this treatise to recommendations and other information contained in the '*Green Book*', or in older editions.

In spite of the important contribution to overall performance of the telephone network, transmission properties of subscribers' lines have not always received adequate attention. At least to some extent this can be explained from history.

Telephony started within local networks, where a number of subscribers was connected to a manual exchange. After some time, longer and longer distances could be bridged, so that local exchanges could be connected with each other. Ultimately the expansion resulted in the present world-wide telephone network. Already at the early start, telephone engineers became aware of the problems caused by losses occurring on telephone lines. At that time, other impairments such as linear and non-linear distortion received less attention.

In the meantime the subscriber's line plant had already grown to an important extent. So it was logical that attention was focussed on low attenuation for the trunk circuits interconnecting exchanges, and that the situation in the subscriber's line plant was more or less accepted, since this plant could not be changed at short notice because of its large size and the costs involved. The average subscriber's line, although being available at any time of the day, is only used for a few calls a day. Trunk circuits, however, are operating with a much better efficiency, due to the concentration of traffic effected in the exchanges. Therefore, care and money spent on trunk circuits will be remunerative. So during a long time the situation in the local network did not change fundamentally; most progress in transmission engineering was in fact firstly made in the trunk network.

In the Netherlands, in the years around 1930, a number of fundamental technical developments made their influence felt in the telephone network. First of all, in that period the general introduction of amplifiers in the network meant many more possibilities to establish long-distance and even international connections [8]. In about the same period intercontinental telephone calls became possible by means of radio [9]. Until that time most exchanges in the network were manually operated and needed a considerable number of operators; only in some large local networks automatic exchanges were in operation. It was gradually realized that automatic switching was the most promising system for the future. In the Netherlands a plan for a nation-wide automatic telephone system was adopted in 1930 [10]. The expected period of realization was 15 years; however, World War II delayed the completion until 1962. This automatization necessitated a more systematic structure of the trunk network.

In the local network it became usual to install cables instead of overhead open-wire lines. The greater loss occurring on the cable was acceptable owing to the reduced loss on trunk circuits. It was even possible to use cables with light-gauge conductors in the local networks, so that economies could be achieved.

It should be noted that the subscriber's line has to accomplish more tasks than only the transmission of speech signals. The 'central battery' (CB) system for supplying feeding current to the microphone in the subscriber's telephone set has found general application. In this system, feeding conditions set additional requirements concerning

subscriber's line resistance. But also signalling had to be transmitted. These additional tasks influenced the transmission design of subscribers' lines and telephone sets.
The introduction of more advanced transmission equipment in the trunk network and the CCI Recommendation, recommending a telephone band extending from 300 to 2500 Hz [11], made it meaningful to improve the sensitivity/frequency characteristics of transmitters and receivers in the telephone sets. Furthermore, the 'anti-sidetone circuit' was introduced [8].
In principle the shape of present local networks is still the same as it was in the thirties, although gradually improvements of minor importance were introduced. But changes are effected very slowly, which is quite understandable because the investments in local cable networks are very high and because these cables have a very long lifetime. At this moment there is even no real prospect that in the near future fundamental changes are to be expected. Only for specific situations application of advanced technologies will possibly offer additional provisions. For the foreseeable future it is to be expected that the majority of subscribers is and will be linked to their local exchange by a pair of metallic conductors. Here we can cite Richards in the Preface of his book *Telecommunication by Speech* [12]: 'that telephone networks have to be treated as evolving organisms and . . . that evolution of their characteristics is slow, although the technologies used in individual items may be very advanced and rapidly changing'. This is the more applicable to local networks. Then economic considerations play an important part.
A CCITT enquiry held in 1964 revealed that from the total investments in public telephone equipment in various countries, an average of 27% is invested in local cable plant [13]. And in 1972 more than a quarter of the total investments of the Netherlands PTT in telecommunication equipment was for local telephone cables [14]. By far the most important part of these costs are to be ascribed to subscribers' lines. These very important investments make it highly desirable to employ subscribers' lines in the overall telephone network such that optimum use is made of the properties of these lines.

1.3 *The subscriber's local system*

Now we will examine the subject of this study in closer detail: the subscriber's line. It is that part of the telephone connection, which links the subscriber's station to the local exchange (see Figure 1.1). In most cases this link is provided by a symmetrical pair of metallic conductors forming part of a multipair cable.* In the Netherlands this

* In principle, the subscriber's line is a direct two-wire connection. For reasons of efficiency usually one or more cross-connection points are traversed. 'Multiple teeing' (several pairs connected together in parallel and thus accessible at several points in the network) is, in principle, not applied in the Netherlands network.

is the case for practically all subscribers, the conductor material being exclusively copper; open wire lines no longer exist. Since about ten years past, only standardized conductors with a diameter of 0.5 mm have in general been installed, but cables with other gauges are still in operation (see Chapter 2).
The telephone set is an instrument for simultaneous two-way conversation. For this reason it has been equipped with a microphone (transmitter) and an earphone (receiver), usually combined in a handset.* So the telephone connection in the subscriber station fundamentally terminates in a four-wire circuit. From a viewpoint of transmission technique, it would be an ideal situation if all interconnections between telephone sets were effected on a four-wire basis. However, for economic reasons this is in general not a realistic solution, and it is not likely to be so in the near future. Therefore, all modern standard telephone sets contain a hybrid circuit, which effects the coupling between the 'four-wire' handset and the two-wire line. The hybrid circuit also provides suppression of the transmission between transmitter and receiver ('sidetone'), for which purpose a balancing network is present, being more or less adapted to the impedances usually seen at the line terminals of the set.
Nearly without exceptions, all over the world, standard telephone sets are equipped with a carbon microphone. As the sensitivity of this type of microphone is dependent on the value of the d.c. feeding current supplied from the central battery, the 'loop resistance' (i.e. the sum of the resistances of both conductors forming the subscriber's line) will influence transmission performance. The equipment installed in the local exchange which supplies the feeding current has a similar effect. This equipment usually consists of a (common) battery and the 'feeding bridge', which is in fact a rather simple filter separating the d.c. feeding circuit from the speech transmission path. Feeding system, subscriber's line and telephone set should, therefore, be adapted to each other. That is why, as concerns some aspects, this combination is often considered as a unit, and is given a specific name, in the CCITT terminology: 'subscriber's local system' [15].
In this study characteristics of telephone sets will only be considered in so far as they are related to the transmission performance of the subscriber's line. Feeding bridges form part of the exchange equipment; their direct influence on the transmission of speech signals is normally included in the overall transmission requirements for the exchange. As the sensitivity of carbon transmitters depends on both loop resistance and feeding system, this aspect will be dealt with in Chapters 3 and 4.
Mention should be made of the fact that d.c. characteristics of feeding bridges usually show a considerable spread. It is perhaps even more important that in the Netherlands network two different feeding systems (battery voltages 48 and 60 V) have found general application. This fact will influence our considerations (Chapter 4). An additional

* There exists a variety of other types of subscribers' stations e.g. 'handsfree telephones', sets equipped with loudspeakers, etc. They constitute only a small minority, and are designed to fit in with the existing telephone network.

The CCITT transmission plan does not go into the details of the national networks. Only overall values for the national part of international connections are recommended and the requirements are given in a statistical form. Connections within a national network fall outside the scope of the CCITT. But, of course, much of the experience and knowledge gained in the CCITT can–and in practice will–also be applied to these connections.
To gain adequate insight into the complex matter of overall transmission performance of a telephone network, it is essential to consider the individual characteristics of the different constituent parts and their variations, but also the role played by these parts in the network and the statistical properties involved.
In transmission planning subscribers' lines play an important part, because of their significant influence on both 'overall loss' and balance return loss. We will, therefore, study the properties of subscribers' lines and especially their contribution to the transmission performance of the telephone system. Furthermore, we will consider possibilities of incorporating the subscribers' lines in the telephone network in an optimum way, taking into account the relevant statistical properties. Our considerations will be restricted to telephony, although naturally other types of signals can be, and in fact in some cases are, transmitted on subscribers' lines. But the public telephone network is still to a predominant extent used for the transmission of telephony, and this is expected to remain so in the near future.
In this study the numerical elaborations and their results will be based on the situation in the Netherlands telephone network. However, the approach and the method of calculation are more generally applicable.

1.2 *Place of subscribers' lines in the telephone network*

The spread of attenuation of speech signals caused by subscribers' lines contributes significantly to the total spread of losses encountered on complete connections. It will be clear that too loud as well as too weak calls will give rise to complaints from the customers. In fact, there is only a rather limited range of overall losses which will give more or less general satisfaction. In Chapter 4 this aspect will be discussed. Obviously the statistical distribution of losses of subscribers' lines is important, because in a telephone connection all combinations of the losses of two subscribers' lines can be expected. On the other hand, the transmission loss of a specific subscriber's line affects every call set up or received by the subscriber concerned.
With regard to echo and stability, we already mentioned the influence of the impedance of the subscriber's line and telephone set on balance return loss. Since usually the loss of the two-wire circuit between local exchange and terminating set (see Figure 1.1a) is rather small (in the Netherlands restricted to a maximum of 3 dB) the impedance conditions as found on subscribers' lines are an important factor in transmission planning.

complication may arise if there is a PBX in the connection between the telephone set and the local exchange. Then the feeding current is usually supplied by a feeding bridge installed in the PBX. This eliminates the effect the loop resistance between PBX and local exchange has on the sensitivity of the microphone. However, problems will arise if automatic regulation in telephone sets is being considered (Chapter 4).
The statistical distribution of the length of subscribers' lines cannot be predicted with reasonable accuracy from existing planning rules. These rules only lay down specific limits, but are not suitable to govern statistical properties. The factual distribution depends not only on the maximum distance in the exchange area, but also on the shape of the exchange area, the subscriber density, the system used in constructing the subscribers' lines, etc. So reliable statistical data can only be obtained by surveying real telephone networks. We will make use of information gathered by the Netherlands PTT in a sampling survey. This will be discussed in Chapter 2.

1.4 *Rating of sensitivity and loss; reference equivalent*

The rating of the performance of telephone sets, whether or not combined with a subscriber's line, has always been a rather critical problem, and only since some years there are prospects of a more conclusive solution [16]. The reason is the complex way in which many factors influence the quality of a telephone call. All these aspects, especially in combination with carbon microphones (with their non-linear behaviour) made it almost impossible to find objective data which characterize the transmission performance of telephone sets adequately. That was the reason why, nationally and internationally, several telephone transmission reference systems were specified over the years, in order to enable a subjective comparison of complete speech links or parts of such links [17-20]. Internationally the newest system is NOSFER (NOuveau Système Fondamental pour la détermination des Equivalents de Référence = New fundamental system for the determination of reference equivalents) [21]. It consists of a standardized test set-up. The test procedure is based on subjective comparison of loudness, under well-defined conditions, e.g. the position of the talker's mouth relative to the microphone is specified, the speech level is controlled, etc. The NOSFER equipment can be divided into a sending and a receiving part. Thus the overall sensitivity of a complete speech path can be measured, as well as the sending and receiving parts separately; the principle is shown in Figure 1.3.
The attenuator in the reference system is adjusted such that in both positions of the switch received speech is heard equally loud. The reference equivalent (RE) of a complete connection or of a sending or receiving part is defined as the value of the additional loss introduced by the attenuator in the reference system. Thus a higher value of RE means a lower sensitivity. Usually the system under test consists of one or two telephone sets with the associated feeding bridge. Also networks representing the sub-

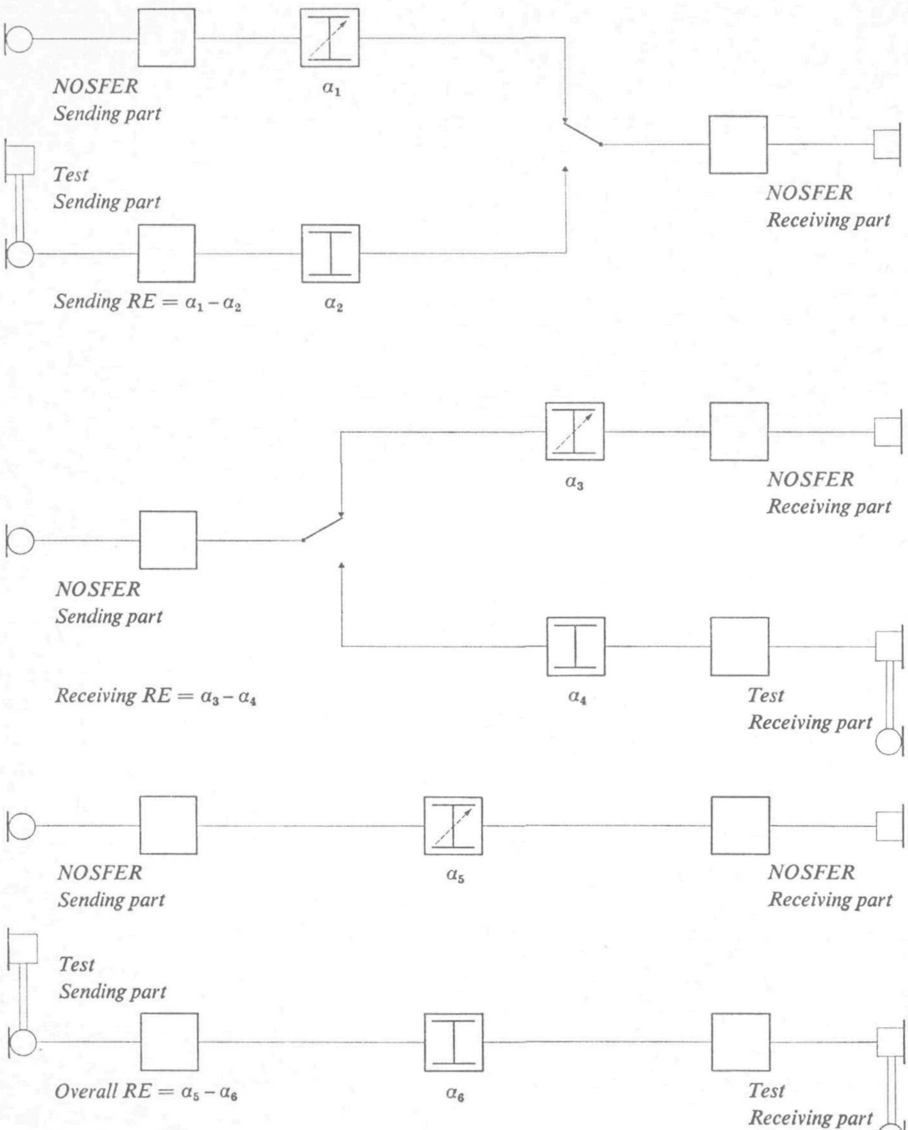


Figure 1.3

scriber's line or other transmission circuits can be introduced. In line with the definition of RE of complete connections the RE of such separate parts could be defined as the difference between the values of RE of a connection with and without these parts.

Systems based on the comparison of sound articulation have been used as well, and are still used sometimes [22]. This very time consuming method has proved impracticable for connections of normal and good quality [23]. Transmission performance of modern telephone networks is such that loudness is the major variable for transmission planning [24].

The concept of reference equivalent offers the advantage that sending and receiving sensitivity can each be specified by one simple quantity; this is important for planning purposes and for making comparisons. However, this system has a drawback, which is fundamental. Separately measured values of the RE of sending and receiving parts can in general not be added to obtain the overall RE. This can best be explained and illustrated by an 'extreme' example.

Suppose the sending part of a telephone set only shows a response at frequencies below, let us say, 1000 Hz, and that the receiving part is only sensitive to frequencies higher than 1000 Hz. The frequency band of the reference system reaches from frequencies considerably lower to frequencies considerably higher than 1000 Hz. Determining the RE for sending and receiving, in both cases the part of the system under test in combination with its counterpart of the reference system will produce some loudness (although not a very acceptable performance). Thus the RE's for sending and receiving will show finite values. But it is clear that for our example a combination of the sending and the receiving part of the system under test will produce no loudness at all. The value of the overall RE thus is infinitely high. This clearly shows that sensitivity/frequency characteristics can affect additivity. Fundamentally, additivity is only assured if the sensitivity/frequency characteristics of the sending and the receiving part of the system under test are identical to those of the reference system. And even then there remain problems concerning the additivity of the losses of the respective parts of a complete link interconnecting two telephone sets. We shall be confronted with this problem in Chapter 3, where the RE of subscribers' lines is calculated. As concerns additivity NOSFER has poor qualities. The characteristics deviate considerably from those of usual modern telephone sets.*

Although loudness is likely the most important variable contributing to transmission performance, it should be borne in mind that the relationship between values of RE and subscribers' opinions is not an unambiguous one. Generally there is a range of subscribers' opinions for each value of overall RE.

1.5 *Echo*

As already indicated in Section 1.1 there is an interaction between overall loss and disturbing effect of echo signals. Therefore we shall give some more attention to echo phenomena which can occur on telephone connections. For this purpose we can use a diagram similar to Figure 1.1a, in which possible echo-paths are indicated (see Figure

* This is why Study Group XII of the CCITT is studying a new system of loudness rating, based on a new Intermediate Reference System with characteristics similar to those of modern telephone sets [25].

1.4). We shall neglect the fact that in the two-wire parts of a connection several points can be expected where impedance irregularities occur, each point giving rise to reflections. Generally (and certainly in the Netherlands) propagation time in these two-wire parts is very short in relation to audible echoes (only a few milliseconds). So it is justified to simplify our diagram by concentrating the reflection points of the two-wire part at the two-wire terminals of the terminating set. In Figure 1.4 we consider possible echoes for a situation in which the subscriber at the left side is talking; but, of course, similar effects occur for the other subscriber, who in this diagram is the listener. In the following we shall give a general description only.

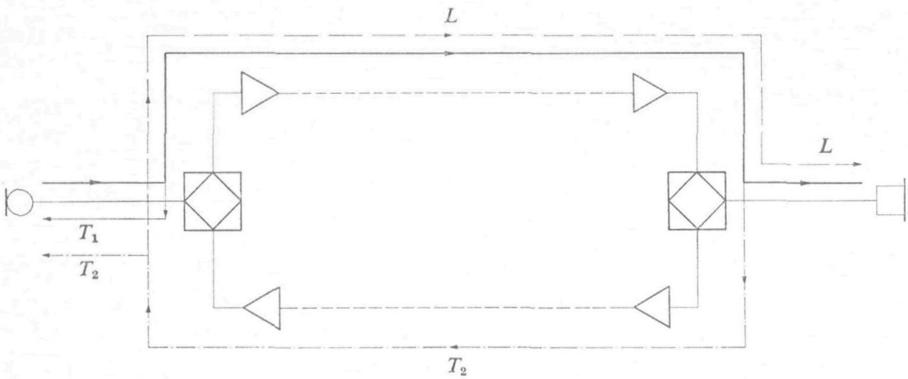


Figure 1.4

The echo signal in Figure 1.4 indicated by T_1 will generally have such a short delay that it is not recognized as a separate echo; echoes are only distinguishable if echo delay is more than about 30 ms [26]. T_1 can therefore be considered as included in the normal sidetone and is usually of less importance. For short overall two-wire connections as indicated in Figure 1.1b, a similar reasoning is relevant; delays are so small that normally distinguishable echoes will not occur.

Disturbing echoes, however, can arise in connections established via the four-wire long distance network. In this case long delays can be involved. In Figure 1.4 the path of the 'talker-echo' is indicated by T_2. The total propagation time along the echo path is known as 'round-trip delay'.

Another type of echo signal is indicated in Figure 1.4 by L, the 'listener-echo'. It is an echo observed by the listener with some delay after the original signal.

Strictly speaking there are many more echo signals, resulting from multiple reflections [27]. However, these echo signals are usually so much attenuated that they can be neglected.

All the echoes originate from impedance mismatches, in our model concentrated at the two terminating sets at both ends of the four-wire path. In a well-designed network at least reasonable values of balance return loss will occur. In Figure 1.4 it can be seen that in the path of the listener echo L two times such a loss is found, whereas for the talker echo T_2 only a single balance return loss is available in the echo path. Therefore, in a modern telephone network listener echo will not be important if talker echo is reduced to an acceptable level [28].*

The limitations to be placed on talker echo need some more consideration. The subjective effect of echo is dependent on several factors, namely: loudness of the echo signal, delay with which it is received and the tolerance to echo exhibited by the subscribers. These points have been investigated and the results were published in the Bell System Technical Journal in 1953 [28]. The fundamental information is reproduced in Table 1.1. The same table is used by the CCITT in calculations on which recommenda-

Table 1.1

One-way propagation time	Attenuation in echo path just satisfactory to 50% of observers
10 ms	11.1 dB
20	17.7
30	22.7
40	27.2
50	30.9

tions concerning echo are based [29]. Table 1.1 shows pairs of values for one-way propagation time (equals half the round trip delay) and attenuation in the echo path; the attenuation represents the median threshold of objection to echo. The attenuation in Table 1.1 refers to the echo path between two-wire ends in the local exchange. However, fundamentally also the sensitivities of the telephone set used by the talker, and the attenuation of the subscriber's line should be included, because they also influence the loudness of the echo received. So, the values in Table 1.1 only give a first indication. The total loudness loss (or reference equivalent) of the complete echo path will be a more appropriate criterion. This point has also been perceived by the CCITT and is now being studied by Study Group XII. Contributions are available from several sources, giving results of more recent investigations [30]. After some problems concerning the use of different criteria have been solved, this information could form the basis for a revision of the relevant recommendation.

On the one hand the new results show the same tendency as those of Table 1.1, namely increasing attenuation against increasing delay, with a steeper slope at the lower values of delay. On the other hand, there is an important difference: for the older results a standard deviation of subscriber's tolerance of 2.5 dB is quoted [28], whereas the

* With data transmission the 'listener echo' can be important because data signals are much more affected by this type of disturbance than speech, especially with shorter echo delays.

recent results indicate standard deviations of 6 and 10 dB. Such a large spread emphasizes the necessity of a statistical approach of the echo problem.
It is worth noting that the total RE of the echo path is in fact the sum of a number of components, e.g. the RE's of the subscriber's local system, the losses of the two-wire trunk circuit, the losses of a number of cascaded four-wire circuits, and the balance return loss at the other end of the four-wire chain. The first mentioned component depends on the situation at the talker's end, whereas the last-mentioned is influenced by conditions at the listener's end. This means that in the echo path a certain subscriber's line can only be involved in one of the two components, i.e. either a contribution to the RE of the subscriber's local system or a certain impact on balance return loss. Consequently, the statistics of these aspects can be studied separately.
The influence of echo on the design of a transmission plan was clearly demonstrated by Huntley [28] in 1953. An important result of his study is that calculations on the probability of objectional echoes showed the need to introduce an additional loss per circuit in the four-wire chain. The magnitude of variations in overall loss in the four-wire loop increases with an increasing number of circuits, because each circuit is assumed to introduce variations in the echo path with a standard deviation of 2 dB. To maintain a fixed limit for the proportion of subscribers observing objectionable echoes, the nominal loss in the echo path should be increased.
The same philosophy is found in the international transmission plan of the CCITT, described in Recommendations G 101 and G 111 [31]. Each international circuit has a nominal loss of 0.5 dB. From Table 1.1 it is quite clear that for very long circuits, with a considerable propagation time, this loss will be insufficient to prevent objectionable echoes. Such long circuits can be expected in intercontinental connections, particularly if they make use of a synchronous-orbit satellite, which introduces a one-way propagation time of about 260 ms. Then additional measures are required, and an 'echo-suppressor' is inserted in the four-wire path. An echo-suppressor is a voice-operated device, in principle permitting transmission of speech signals in only one direction of the four-wire circuit. The performance of this equipment is specified by the CCITT [32].
In fact, echo-suppressors are needed in circuit chains with a one-way propagation time longer than about 25 ms; with delays longer than this value, too much loss in the speech path would be needed to suppress echo sufficiently. This particularly applies to modern networks, which show the tendency to reduce the loss which will occur in long distance connections, in order to meet the subscriber's preference. But even if an echo-suppressor is introduced, a minimum value of balance return loss is required, in order to make the echo-suppressor function properly.

1.6 *Stability*

Circuit stability is closely related to the phenomenon of echo, as can be seen in the diagram of Figure 1.4. The echo path indicated by L contains the loop which can give rise to instability. In general instability will be rare if echo conditions are satisfactory. However, it should be realized that the effect of echo is dependent on some weighted average of loss in the speech frequency band (loudness), whereas with regard to stability each individual frequency should be considered. It should be observed in this respect that values of balance return loss can vary considerably with frequency.

In fact, transmission quality will also be seriously degraded in 'near-singing' conditions ('hollowness' of speech). Therefore, some stability margin is required; a minimum loss in the four-wire loop of 6 dB has been suggested for a satisfactory transmission performance [33]. For connections over shorter distances, in which the prevention of objectionable echoes only requires a relatively low value of loss, the stability margin should receive special attention. So, normally, during a telephone conversation 'singing' of the connection should be almost impossible.

A much more serious possibility of instability occurs if one two-wire end or even both ends of the connection are not properly terminated, which will give rise to low values of balance return loss. Such conditions can appear in an automatically switched network during setting-up and clearing of a connection [34]. During these periods two-wire circuits in switching centres can be 'open' for longer or shorter time, depending on the switching and signalling system used and on special measures introduced to ensure stability. Although during these periods the influence on speech transmission on the circuit concerned is not relevant because the connection is incomplete, it is nevertheless important to prevent 'singing' for other reasons e.g. overloading of multichannel carrier systems, crosstalk, disturbing VF signalling, etc.

A source of similar improper terminating conditions can be found in the usual telephone set. During the development of telephone systems signalling and speech transmission aspects have been mixed up especially in the subscriber's station. So it is common practice that the hook switch has two functions. At the end of the call it indicates that the subscriber has replaced the handset and that the connection can be released, but at the same time the transmission circuit in the set is disconnected from the line. In this condition the end of the subscriber's line is nearly completely 'open' (except for the ringer circuit which has usually a high impedance in the speech frequency band). It takes some time before the automatic switching system in the local exchange has detected the 'on-hook' condition. During this process a dangerous situation with regard to stability arises, owing to the bad terminating conditions; in certain cases the two-wire trunk circuit can be nearly completely 'open'. It will again take some time before this situation is recognized in exchanges of higher level and the four-wire loop can be interrupted, which effectively eliminates the risk of instability.

In practice bad terminating conditions cannot completely be precluded. But the tele-

phone set could be designed such that in the 'on-hook' condition in the telephone band a reasonable impedance is offered to the line.* Similar actions are conceivable in switching centres. In this connection it is appropriate to note that short periods with bad terminating conditions do not harm, because it takes some time before 'singing' obtains a level which can be disturbing. Periods shorter than several decades of milliseconds (e.g. switching times of relays) can usually be neglected. So it is clear that the risk of instability during setting-up and release of a connection could to a large extent be reduced by special measures in switching and signalling systems. Some possibilities have been indicated by the CCITT for international connections [35].
As already mentioned, as far as short connections are concerned, stability can become a point of consideration in transmission planning. In countries with only small national distances (as is the case in the Netherlands) the loss required in the four-wire chain for international connections, in order to prevent objectionable echoes, may not be wanted for national calls. This is the reason why national connections can be supplied with a lower overall loss. In fact such a solution is applied in the Netherlands network [36]. For national connections an additional favourable condition is that all the equipment is usually controlled by one and the same administration, which enables the application of well-defined stability measures in an efficient way.
However, additional switching and signalling aspects are not the subject of this treatise. Our attention will be focussed on the influence of the subscriber's line and the telephone set in the normal speaking condition ('off-hook' condition). In that case it is important to prevent 'near singing' conditions during telephone conversation, whereas stability should be considered in situations in which terminating conditions at the other end are inadequate (e.g. the other subscriber has released first). With both aspects of the stability problem the impedance of the subscriber's line (terminated by a telephone set), as seen from the local exchange, plays an important part. The statistical properties of this impedance and a method to find optimum conditions with respect to 'echo' and circuit stability are discussed in Chapter 5.

References Chapter 1

1 Afd. S en B, PTT, *PTT in cijfers*. In: Aangetekend, 8 no. 174 (1975), p. 5.
2 ITU, *List of definitions of essential telecommunication terms*. Part 1: General terms, telephony, telegraphy (ITU, Geneva, 1961).
3 Bolle, A. P., *Stabiliteit van negistoren*. In: Het PTT-Bedrijf, XII no. 2 (1963), pp. 73-79.

* It seems at least recommendable to take into consideration this possibility when studying the design of new telephone sets.

4 Bergmann, K., *Lehrbuch der Fernmeldetechnik*, p. 115 (Schiele & Schön, Berlin, 1973).
5 Richards, D. L., *Telecommunication by speech*, Chapter 3 (Butterworths, London, 1973).
6 CCITT, *Green Book*, Vol. III-1, Recommendation G. 141, p. 58 (ITU, Geneva, 1973).
7 Richards, D. L., *Telecommunication by speech*, pp. 526-527 (Butterworths, London, 1973).
8 Hendriks, H. A., *De ontwikkeling van de verbindingswegen in het Nederlandse telefoonnet*. In: Het PTT-Bedrijf, XI no. 3/4 (1962), pp. 160-186.
9 v. d. Berg, D., *Eindapparatuur voor radiotelefoonverkeer op lange afstand*. In: Het PTT-Bedrijf, V no. 1 (1952), p. 40.
10 v. Hemert, D., *De automatisering van de telefoon in Nederland gedurende het tijdvak 1927-1940*. In: Het PTT-Bedrijf, XI no. 3/4 (1962), pp. 100-121.
11 CCI, *Comité Consultatif International des Communications Téléphoniques à grande distance, Plenary Session 1929*. English edition, p. 121.
12 Richards, D. L., *Telecommunication by speech*, Preface (Butterworths, London, 1973).
13 CCITT, Handbook *Local telephone networks*, Chap. I, p. 3 (ITU, Geneva, 1968).
14 Bordewijk, J. L. et al., v. d. Berg, D., Horn, W. *Communicatiestad 1985, Elektronische communicatie met huis en bedrijf*, p. 33 (Stichting Toekomstbeeld der techniek, 's-Gravenhage, 1973).
15 CCITT, Handbook *Local telephone networks*, Terminology, p. 8 (ITU, Geneva, 1968).
16 CCITT, *Green Book*, Vol. V, pp. 215-259 (ITU, Geneva, 1973).
17 Martin, W. H. and Gray, C. H. G., *Master reference system for telephone transmission*. In: The Bell System Technical Journal, 8 no. 3 (1929), pp. 536-559.
18 CCIF, *Green Book*, Vol. IV, pp. 27-43 (ITU, Geneva, 1956).
19 Koop, E. J., *The transmission performance preferences and tolerances of telephone users*. In: The Telecommunication Journal of Australia, 18 no. 1 (1968), pp. 28-39.
20 Richards, D. L., *Telecommunication by speech*, pp. 6-13 (Butterworths, London, 1973).
21 CCITT, *Green Book*, Vol. V, Recommendation P. 42, pp. 43-67 (ITU, Geneva, 1973).
22 CCITT, *Ibidem*, Recommendations P. 12 and P. 45, pp. 8-11 and 72-75.
23 Richards, D. L., *Telecommunication by speech*, p. 169 (Butterworths, London, 1973).
24 Sullivan, J. L., *A laboratory system for measuring loudness loss of telephone connections*. In: The Bell System Technical Journal, 50 no. 8 (1971), pp. 2663-2739.
25 CCITT, *Green Book*, Vol. V, p. 227 (ITU, Geneva, 1973).
26 Richards, D. L., *Telecommunication by speech*, p. 103 (Butterworths, London, 1973).

27 v. Zoest, W. H., *Echosignalen*. In: Het PTT-Bedrijf, VII no. 3 (1956), pp. 77-84 and VII no. 4 (1957), pp. 128-133.
28 Huntley, H. R., *Transmission design of intertoll telephone trunks*. In: The Bell System Technical Journal, 32 no. 5 (1953), pp. 1019-1036.
29 CCITT, *Green Book*, Vol. III-2, pp. 556-559 (ITU, Geneva, 1973).
30 CCITT, *Green Book*, Vol. V, pp. 158-174 (ITU, Geneva, 1973).
31 CCITT, *Green Book*, Vol. III-1, pp. 3-6 and 13-16 (ITU, Geneva, 1973).
32 CCITT, *Ibidem*. Recommendation G. 161, pp. 72-98.
33 Richards, D. L., *Telecommunication by speech*, p. 304 (Butterworths, London, 1973).
34 Hooijkamp, C., *Considerations governing the choice of the equivalent for a telephone circuit*. In: Philips Telecommunication Review, 19 no. 2 (1958), pp. 74-94.
35 CCITT, *Green Book*, Vol. VI-1, Recommendation Q. 32, pp. 69-71 (ITU, Geneva, 1973).
36 Huis, T., *De stand van zaken betreffende de studie ten behoeve van een nieuw dempingsplan*. In: Data, 73 no. 2 (1972), pp. 23-32.

2 Results of a sample survey of subscribers' lines *

2.1 *The sample*

In 1966 the Local Lines Section of the Central Transmission Branch of the Netherlands PTT organized a survey in order to obtain information about subscribers' telephone lines. At that time no reliable statistical information was available; it was therefore decided to collect data from a random sample of subscribers. The number of subscribers to be included in the survey was chosen to be about 1600, which number was expected to allow sufficiently accurate estimates of the characteristics of the total population.

A sample representative of the population of all subscribers in the Netherlands telephone network (at that time about 1.6 million) was prepared by the Central Statistics Branch of the Netherlands PTT. To select the sample use was made of the telephone directories of the whole telephone system. Thus the population from which the sample was drawn, comprised all the subscribers, with some minor exceptions, e.g. public call boxes and subscribers with a 'secret' telephone number, both of which are not listed in the directories. However, the number of such exceptions is relatively small and there is in most cases no reason to assume that the characteristics of these subscribers' lines will deviate systematically from those of other subscribers. Therefore, it is believed that their exclusion will have a negligible effect on the validity of the results of the survey.

The subscribers to be included in the survey were obtained by selecting a certain entry of the second columns on every third page in each directory. In this way a very good geographical distribution was arrived at. The selected subscribers were next grouped according to the telephone district involved, and the required information from each district was collected by the Local Lines Section. Special circumstances made it impossible to obtain the required data concerning subscribers' lines in the local network of Amsterdam. This could imply that the sample is less representative, because the local network of Amsterdam contained about ten percent of all subscribers in the Nether-

* A first and concise report on the results of this survey has meanwhile been published [1]. The more elaborate results given in this chapter are derived from the same basic information. Some results presented now show minor deviations from those published earlier. Such deviations result from a more detailed and profound processing of the data available. However, the results and conclusions presented in [1] are not essentially affected.

lands. To obtain an insight into the possible effect of the absence of Amsterdam subscribers in the survey, particular attention will be focussed on the results of other large local networks in the detailed study of the data gathered.

2.2 *The data*

The main purpose of the survey was to obtain a good insight into the statistics of the basic transmission characteristics of subscribers' lines. To that end first of all two rather simple, but essential data were selected: length and d.c. loop resistance of the subscriber's line. This information was generally not available in this form, but had to be derived from local records and route maps.

The length of the selected subscribers' lines was made available in values rounded to the nearest 0.1 km, whereas values of loop resistance were rounded to the nearest 10 Ω. In addition the number of metering pulses used by the subscriber during the year preceding the survey was recorded. This information provided some measure of the amount of telephone traffic originating from this subscriber.

The data collected from the different telephone districts were, after a first preparation, submitted to a preliminary examination by the Local Lines Section. As an unexpectedly high number of lengths exceeding the 5 km limit of the existing planning rules was observed, the Local Lines Section referred the data of these lines to the point of origin for checking purposes and in order to have more complete information available.

The data thus gathered in the survey were made available to us, and elaborated in detail at the Dr. Neher Laboratories of the Netherlands PTT. First of all the relation between length and loop resistance was checked, which should for each line correspond to really existing cable. The checks on lines longer than 5 km and on the relation between length and loop resistance revealed that in the data originating from a certain sector in the network–concerning about 0.9% of the survey–a systematic error had been made. This error could easily be corrected.

Other discrepancies between length and loop resistance were further investigated. In so far as these discrepancies could be traced the data were corrected accordingly, as was done with data on some lines of which the new information showed that they had erroneously been listed as being longer than 5 km.* These corrections concerned in total about 0.6% of the survey. Lines of which the discrepancies could not be eliminated were excluded from the sample (about 0.6%).

Ultimately the sample comprised a total number of 1433 subscribers' lines. The contents of this chapter are based on data collected about these lines.

* Strictly speaking this last correction is not consistent, because such a check had not been made on the lines shorter than 5 km. So it may be possible that lines longer than 5 km are slightly underrepresented.

2.3 *Distribution of length*

The data on the lengths found in the survey are listed in Table 2.1, while in Figure 2.1 a histogram is plotted. Figure 2.2 shows the cumulative distribution (solid curve). In Figure 2.3 the same distribution is drawn, but to a scale on which a straight line corresponds to a Gaussian ('normal') distribution.

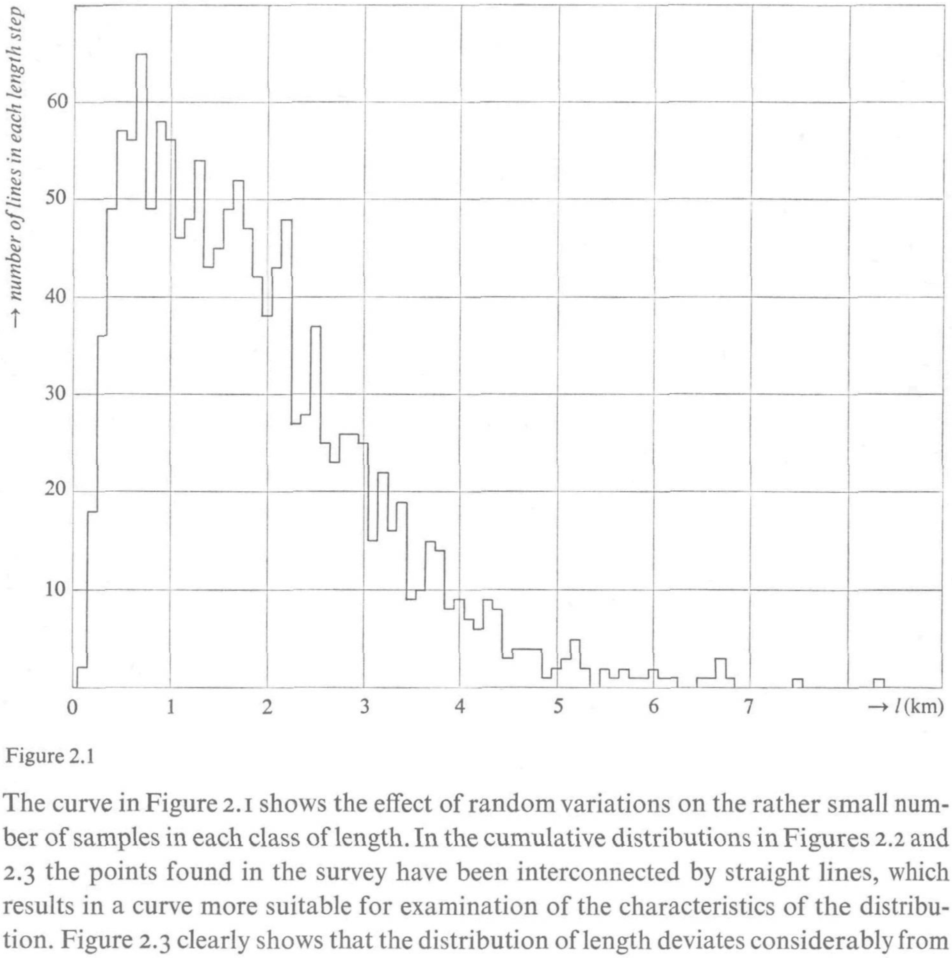


Figure 2.1

The curve in Figure 2.1 shows the effect of random variations on the rather small number of samples in each class of length. In the cumulative distributions in Figures 2.2 and 2.3 the points found in the survey have been interconnected by straight lines, which results in a curve more suitable for examination of the characteristics of the distribution. Figure 2.3 clearly shows that the distribution of length deviates considerably from a Gaussian distribution. This was to be expected, because physically the distribution of length has an absolute limitation at line length zero. A remarkable feature of the distribution is that, even after corrections have been made, the percentage of lines longer than 5 km is still about 2%, whereas only some tenths of a percent had been expected [2]. Another interesting aspect is that very short lines were very rare in the survey: the number of samples in class 0 (length < 0.05 km) was zero, and in the next class (0.05-0.15 km) only two.

Table 2.1

Length rounded to nearest 0.1 km	Number of lines in each length step	Cumulative percentage	Length rounded to nearest 0.1 km	Number of lines in each length step	Cumulative percentage
0.0	–	0 %			
0.1	2	0.14	3.6	10	91.35%
0.2	18	1.40	3.7	15	92.39
0.3	36	3.91	3.8	14	93.37
0.4	49	7.33	3.9	8	93.93
0.5	57	11.3	4.0	9	94.56
0.6	56	15.2	4.1	7	95.05
0.7	65	19.7	4.2	6	95.46
0.8	49	23.2	4.3	9	96.09
0.9	58	27.2	4.4	8	96.65
1.0	56	31.1	4.5	3	96.86
1.1	46	34.3	4.6	4	97.14
1.2	48	37.7	4.7	4	97.42
1.3	54	41.5	4.8	4	97.70
1.4	43	44.5	4.9	1	97.77
1.5	45	47.6	5.0	2	97.91
1.6	49	51.0	5.1	3	98.12
1.7	52	54.6	5.2	5	98.46
1.8	47	57.9	5.3	2	98.60
1.9	42	60.9	5.4	–	98.60
2.0	38	63.5	5.5	2	98.74
2.1	43	66.5	5.6	1	98.81
2.2	48	69.9	5.7	2	98.95
2.3	27	71.7	5.8	1	99.02
2.4	28	73.7	5.9	1	99.09
2.5	37	76.3	6.0	2	99.23
2.6	25	78.0	6.1	1	99.30
2.7	23	79.6	6.2	1	99.37
2.8	26	81.4	6.3	–	99.37
2.9	26	83.3	6.4	–	99.37
3.0	25	85.0	6.5	1	99.44
3.1	15	86.0	6.6	1	99.51
3.2	22	87.6	6.7	3	99.72
3.3	16	88.7	6.8	1	99.79
3.4	19	90.02	6.9	–	99.79
3.5	9	90.65	>7.0	3	100.00

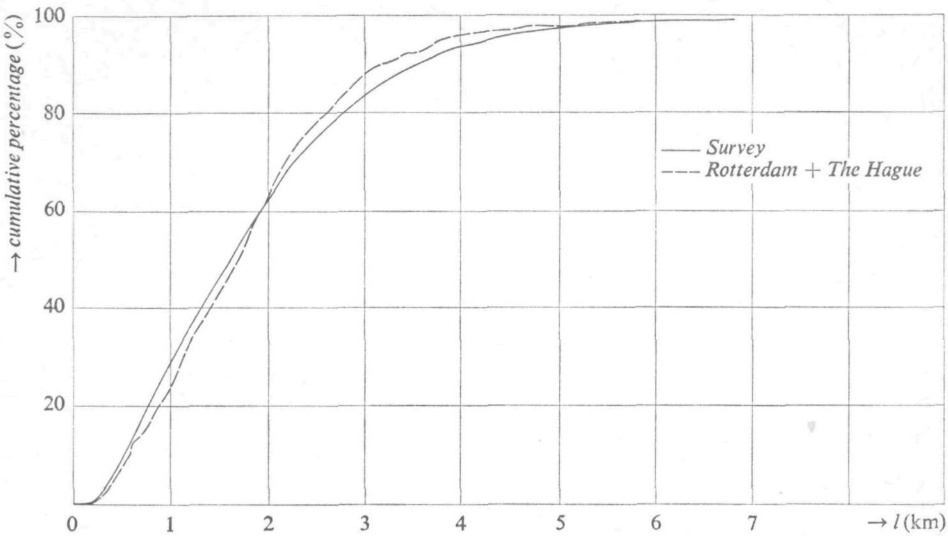


Figure 2.2

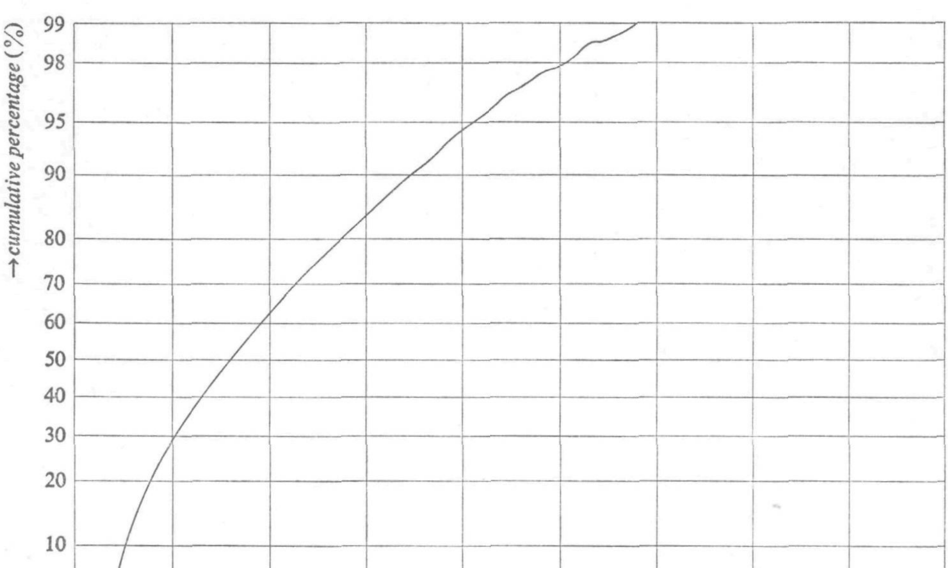


Figure 2.3

The mean value and the standard deviation of the distribution of length were calculated:

$$m_l = \frac{\sum_{i=1}^{N} l_i}{N} = 1.847\ \text{km} \tag{2-1}$$

$$s_l = \sqrt{\frac{\sum_{i=1}^{N} (l_i - m_l)^2}{N}} = 1.251\ \text{km} \tag{2-2}$$

In these equations N is the total number of samples.
We next calculate the 95% confidence limits for the mean value: $\pm$ 0.065 km.
Now it may be useful to consider the distribution of line length as found in large local networks, namely Rotterdam and The Hague. A rough comparison with the results of the total sample can be made in Figure 2.2, where a dotted line indicates the cumulative distribution of lengths as found for Rotterdam and The Hague together.
The mean and standard deviation of lengths in Rotterdam and The Hague together were calculated: $m'_l = 1.83$ km (95% confidence limits $\pm$ 0.14 km)
$s'_l = 1.24$ km.

These values are very close to those obtained for the complete sample.
For a more detailed investigation the data of the survey were divided into two groups: one containing the data of Rotterdam and The Hague, the other with data concerning the rest of the country. We pose the hypothesis that both groups of samples are drawn from a population with the same distribution function. To check the validity of this hypothesis, we compose a contingency table (Table 2.2) and apply a chi-square test [3, 4, 5]. In Table 2.2 classes of length have been pooled in such a way that the new cell frequencies are sufficiently high. Now we calculate the value of chi-square. This is a weighted measure of the deviation of the actual cell frequencies from the expected frequencies, the latter being derived from the marginal frequencies.
The calculated value for chi-square is $\chi^2 = 21.1$
For the 2 x 17 classification table we can test the significance of the deviations by calculating the probability of exceeding the value 21.1 in a chi-square distribution with 16 degrees of freedom. This probability is 0.175, which means that the deviations can reasonably be ascribed to variations resulting from random sampling; the probability of finding even higher values is 17.5%. We conclude that the deviations are not sufficiently significant to reject our hypothesis that both groups of lines are drawn from a population with the same distribution function. Or in other words: the distribution of length found in the large local networks does not deviate significantly from the distribution of the total sample.* As there is no reason to assume that the situation in Am-

* For a similar result in Germany, see Par. 2.4.5.

sterdam differed substantially from that in other cities, it is likely that the absence of Amsterdam subscribers in the survey will not have an important influence on the validity of the overall results of the national survey.

Table 2.2

Length	Number of lines in Rotterdam + The Hague	Rest	Total
0.0–0.3 km	8	48	56
0.4–0.5	17	89	106
0.6–0.7	19	102	121
0.8–0.9	20	87	107
1.0–1.1	27	75	102
1.2–1.3	19	83	102
1.4–1.5	20	68	88
1.6–1.7	21	80	101
1.8–1.9	23	66	89
2.0–2.1	25	56	81
2.2–2.3	18	57	75
2.4–2.5	14	51	65
2.6–2.8	16	58	74
2.9–3.1	15	51	66
3.2–3.5	8	58	66
3.6–4.2	12	57	69
$\geqslant$4.3	8	57	65
Total	290	1143	1433

2.4 *Comparison with results of other surveys*

In this section we will compare the distribution of subscriber's line length, as found in Section 2.3, with the results of an older survey concerning the Dutch network. Moreover, a confrontation with results of surveys undertaken in networks in other countries seems worthwhile. For this purpose we will use information published about surveys in Australia, the USA, the United Kingdom and Western Germany.

2.4.1 *Earlier survey in the Netherlands*

A couple of years before the survey under discussion was conducted, the Local Lines Section of the Netherlands PTT collected information on the length of subscribers' lines in 56 local networks. In this survey mainly rural networks were involved. That

was the reason why the results could not be considered representative of the national situation. Longer lines in particular were expected to be overrepresented.
The total number of subscribers covered by this survey amounted to about 34000. The relevant distribution of length is shown in Figure 2.4, together with the distribution found in Section 2.3 (broken curve). The similarity of the two curves is remarkable,

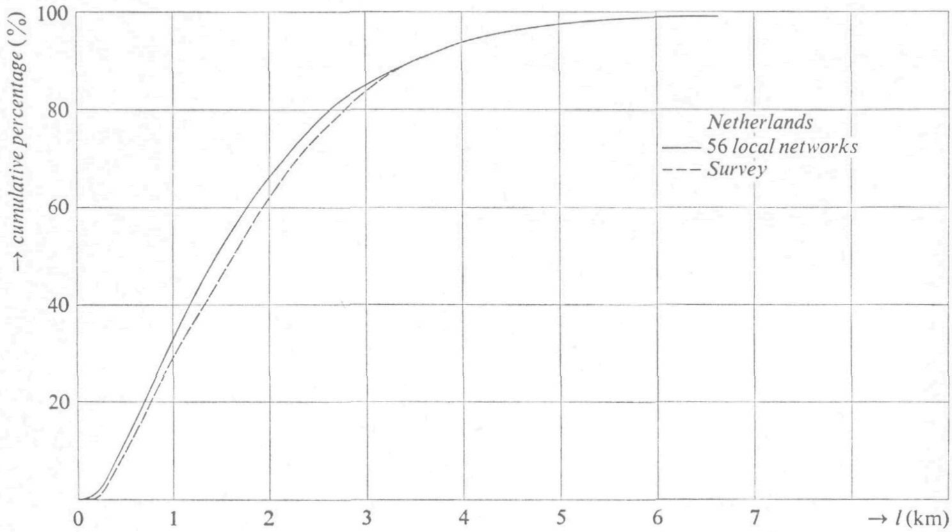


Figure 2.4

especially as far as the longer lines are concerned. Apparently the current supposition that rural networks have a relatively large number of long subscribers' lines is not confirmed. Here we have an indication of a similar nature as was found for large cities, namely that the distribution of length does not seem to be predominantly influenced by the fact whether the network is situated in a metropolitan area or in a rural one.

2.4.2 *Survey in Australia*

Kitchenn reported on a transmission survey of subscribers' telephone services, conducted in Australia in 1965 [6]. It concerned a very comprehensive survey about the transmission performance of local telephone networks and telephone sets. A sample with a nominal size of 1000 was chosen from the telephone directories, in a similar way as for the Netherlands survey. A long list of data on each subscriber was collected, including subscribers' opinions.
For our purpose the most interesting feature is the distribution of length found for a sample of 985 subscribers' lines, which is reproduced in a cumulative curve in Figure 2.5. There is a good resemblance to the Netherlands distribution (dotted line in

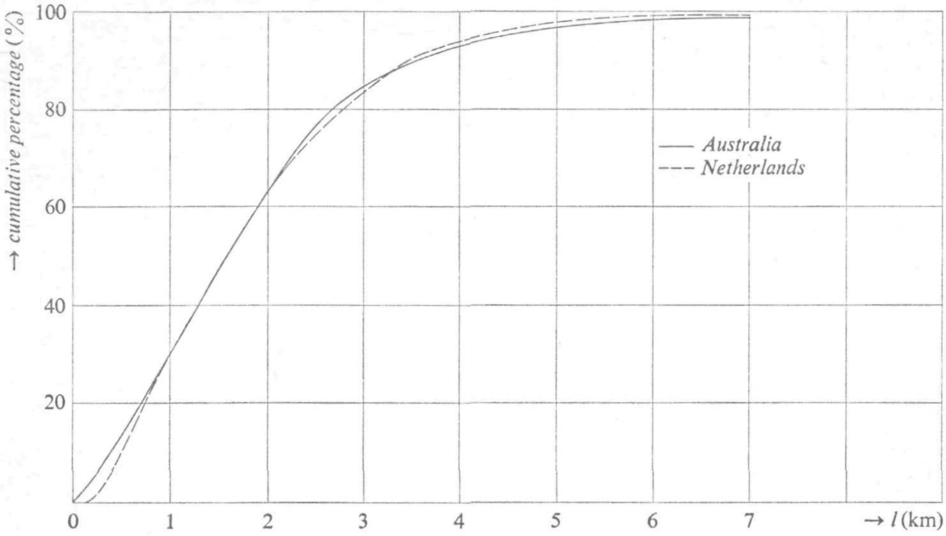


Figure 2.5

Figure 2.5). However, for lengths greater than 4 km there is apparently a difference. Perhaps this difference can be explained by the enormous difference between the average population density in both countries, which makes it reasonable to expect more longer lines in Australia.

Another interesting aspect of the Australian survey is that it also covered the distance from the local exchange to the subscriber's premises, measured along a straight line ('radial distance', *r*). Kitchenn calculated the ratio between cable length ('route distance', *l*) and radial distance and presents this ratio in a diagram as a function of radial distance (see Figure 2.6). In his book on network planning [7] H. Kremer already

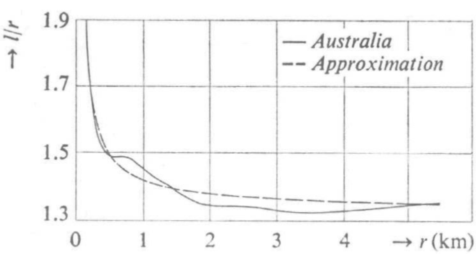


Figure 2.6

pointed out that there is a relation between cable length and radial distance, which can be expressed by the general formula

$$\frac{l}{r} = C_1 + \frac{C_2}{r} \tag{2-3}$$

where l is the cable length and r is the radial distance, both in km. For normal situations Kremer quotes the following values for the constants: $C_1 = 1.3-1.4$ and $C_2 \approx 0.1$ km. It is striking that the curve found by Kitchenn can be approximated very well by formula (2–3) if $C_1 = 1.34$ and $C_2 = 0.08$ km (dotted line in Figure 2.6). For the majority of lengths the ratio is very close to the average value 1.4; only for very short lines the ratio is substantially larger, but then an approximated value of 1.4 will only result in a small absolute error in length (or distance).
Formula (2–3) indicates a minimum value for the length, which is equal to C_2. In this connection we should realize that formula (2–3) only gives average values. Of course for each class of distance the ratio can vary between an absolute lower limit of 1 (in the extreme case that the cable is laid along a straight line) and values considerably higher than the average, if the cable follows a roundabout route (see also Paragraph 2.4.3). Strickly speaking this (unknown) spread in the values of the ratio should be taken into account when considering the relation between statistical distributions of length and radial distance. However, the (average) values given appear to be sufficient for converting the distribution of radial distance into the distribution of line length (and vice versa) with reasonable accuracy, as could be verified in a diagram in Kitchenn's article, which presented both distributions.

2.4.3 *Surveys in the USA*

In the United States of America a survey of Bell System subscribers' lines was undertaken in 1960. Hinderliter published a brief report on the results [8]. In 1964 a similar survey was conducted and Gresh published extensive results [9]. His publication also contains more detailed information concerning the 1960 survey and he compares the results of both surveys. An important general conclusion was that in many respects the composition of the subscriber's line plant changes only slowly.
Basically the surveys mentioned comprised a random sample selected from the population of main stations. The numbers of lines included in the survey were 1000 and 1100 respectively. For both surveys the distributions of length are given in Figure 2.7, curves *a* and *b*.
Information on subscribers' lines in another System in the USA was published by Davis [10, 11]. He describes the results of a sample of 1000 subscribers' lines in the General System surveyed in 1968. As far as the distribution of length is concerned (see curve *c* in Figure 2.7) he found that the lower 60% is very similar to the Bell distribution. From the remaining 40% Davis concludes that the 'General' customers are usually farther from the exchange than 'Bell' customers.
Comparison with the results of the Netherlands survey shows that subscribers' lines in the USA are substantially longer. Planning rules in the USA Systems seem to be based

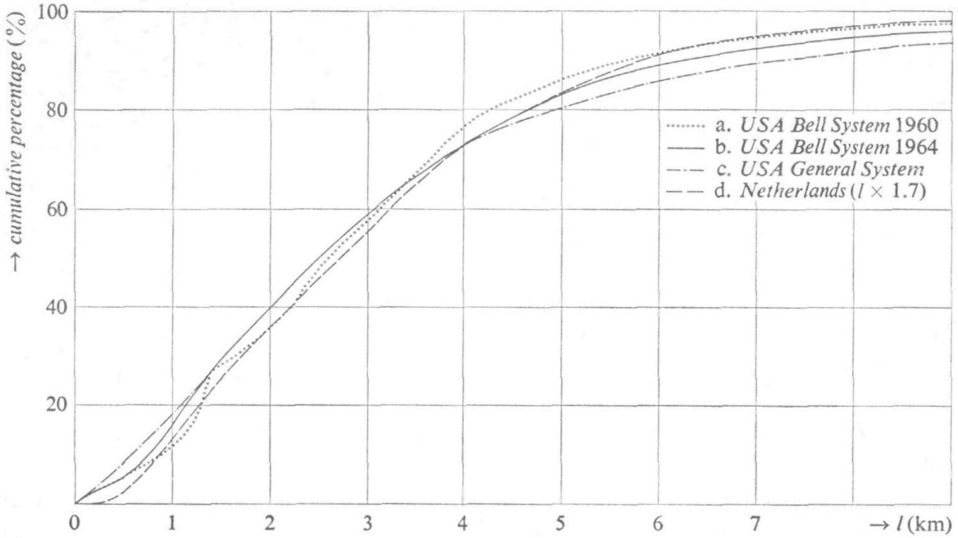


Figure 2.7

on larger exchange areas where loading is applied to subscribers' lines longer than 5.4 km. However the shape of the cumulative distribution curves is almost similar to that concerning the Netherlands, as can be seen from curve *d* in Figure 2.7 which shows the Netherlands distribution in case all the lengths are multiplied by a factor 1.7.

Another interesting point in Gresh's publication [9] is the distribution of the ratio between length and radial distance as found in the 1960 and 1964 surveys in the Bell System. The results for both surveys were nearly the same; in Figure 2.8 the average is given. Of course, the ratio has a lower limit of 1, but also values of up to 3 were found.

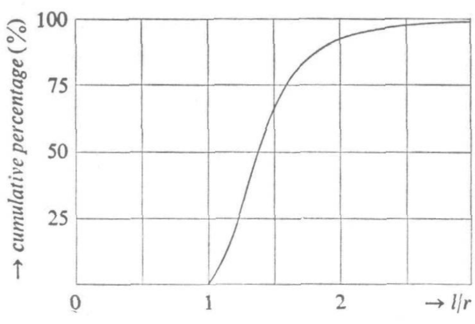


Figure 2.8

This distribution is the result of two phenomena: spread occurring for each class of length and the variation of the mean value of the ratio as a function of distance (see

Paragraph 2.4.2). These two influences cannot be separated in Figure 2.8, but it is estimated that the first-mentioned effect contributes considerably to the total spread in the distribution.

From cumulative distribution curves for radial distance and length in Gresh's publication we can roughly deduce the ratio as a function of distance; a similar tendency as in Figure 2.6 was found, i.e. higher values at shorter distances. The overall mean value of the ratio between length and radial distance in the Bell System was 1.45 in the 1960 survey and 1.50 in the 1964 survey. Davis [10, 11] reported a mean value of 1.35 for the General System. This lower value can perhaps be explained by the fact that in the General System there are more long lines, which show a tendency towards lower values for the ratio between length and radial distance.

2.4.4 *Survey in the United Kingdom*

Information on a comprehensive investigation made by the Post Office is given in [12]. As a first step towards a detailed study of the costs of subscribers' lines, two large random samples were drawn from the total telephone population. The samples, surveyed in 1958 and 1962 respectively, each concerned about 8800 subscribers. The information collected included the radial distance. The distributions of radial distance resulting from these surveys were very much alike. Apparently, the statistical distribution of distance changes only slowly; an interval of four years caused no appreciable change. The mean value of radial distance was 0.74 miles. Richards [13] indicates the same mean value for a survey conducted in 1964/65; whereas he reports a value of 1.01 miles (1.63 km) for the mean line length. The ratio between these mean values,

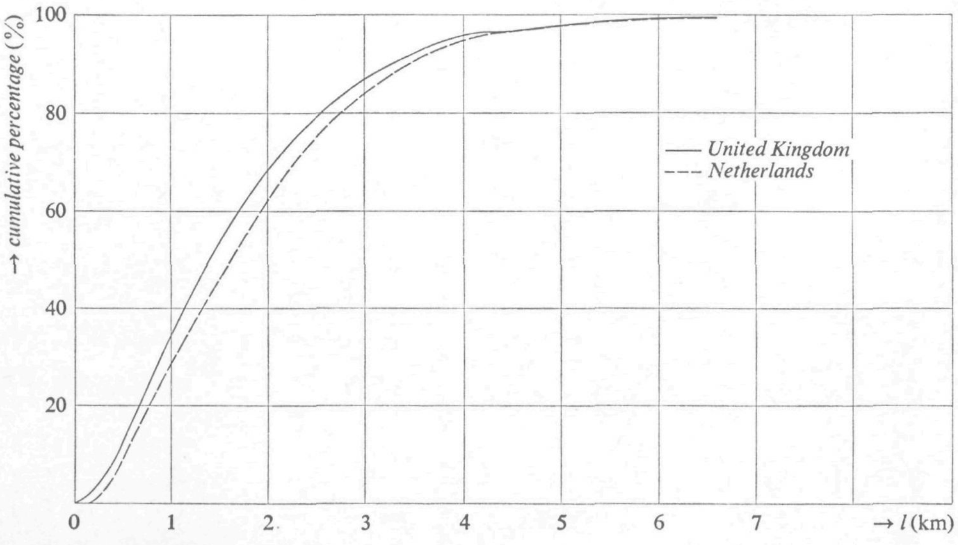


Figure 2.9

i.e. 1.36, is in good agreement with the results found for the ratio between line length and radial distance in the Australian survey (Paragraph 2.4 2). So, it seems possible to use these Australian results, approximated by formula (2–3), to translate the detailed distribution of radial distance given in [12] into a reasonable estimate of the distribution of length. The resulting distribution of length for the combined surveys (in total about 17500 subscribers) is given in Figure 2.9. There is a reasonable resemblance to the Netherlands distribution (dotted line in Figure 2.9).

2.4.5 *Information from Western Germany*

Sattelberg published the distribution of length of subscribers' lines in 59 local networks [14]. But Kremer [15] already pointed out that the results cannot be considered representative of the national situation, because the sample was not random but contained mainly large networks. Nevertheless, the distribution is reproduced in Figure 2.10, curve *a*.

At the International Seminar on National Telephone Transmission Planning in 1970, Dehmer and Wirz presented another distribution [16]. The way in which the information was collected is not known. As concerns the shorter lines, this distribution (Figure 2.10, curve *b*) shows a good agreement with Sattelberg's results. On the other hand, Kremer's assumption that longer lines in Sattelberg's distribution were overrepresented seems to be confirmed. The German distribution deviates slightly from that of the Netherlands (Figure 2.10, curve *c*); apparently there are somewhat more short and long lines. But in general there is a reasonable agreement, although it seems that on an average German subscribers' lines are a little shorter.

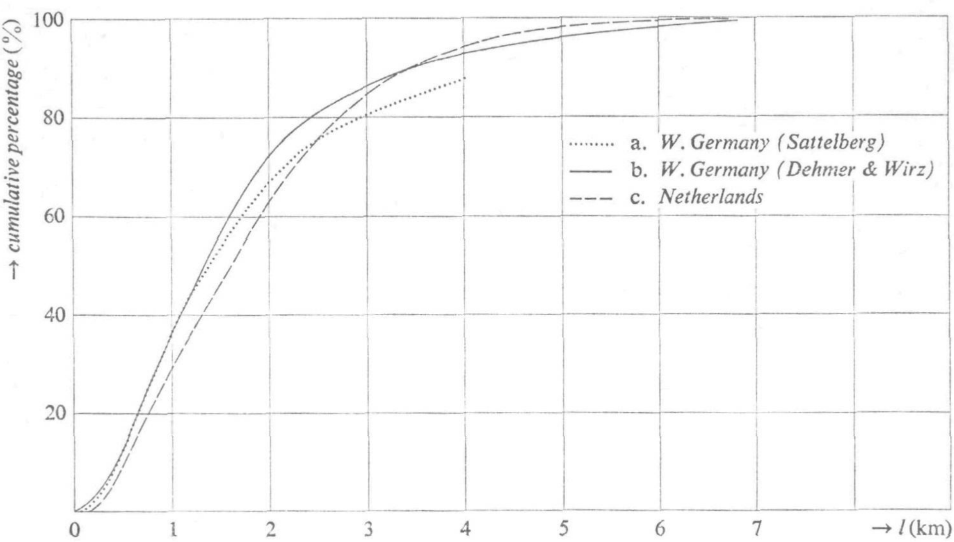


Figure 2.10

Angrick reported on a survey conducted in 1958 in order to obtain the mean value of the length of subscribers' lines [17]. This survey involved 69 selected local networks of different size, with a total of 168000 subscribers. A mean value of 1.75 km was found. This value is only slightly lower than the mean value in the Netherlands survey. Moreover, Angrick observed that it is remarkable that the mean value of length shows such a small dispersion over networks with different numbers of subscribers. This is a conclusion with a similar tendency as found for the Netherlands survey (last part of Section 2.3; Paragraph 2.4.1).

2.4.6 *Concluding remarks*

Resuming the results of the comparisons we made, we can conclude that obviously planning rules for subscribers' lines in a number of countries do not differ very much or at least result in a distribution of length rather similar to the distribution found for the Netherlands situation. The results found in the USA show substantially longer lines, which can easily be explained from quite different planning rules. However, apart from a constant factor in length, the shape of the distribution of subscriber's line length shows a remarkable resemblance to the Netherlands results.

2.5 *Distribution of loop resistance*

Next we shall consider the data on loop resistance (R_l) as collected in the Netherlands survey. First of all, the cumulative distribution is given in Figure 2.11.

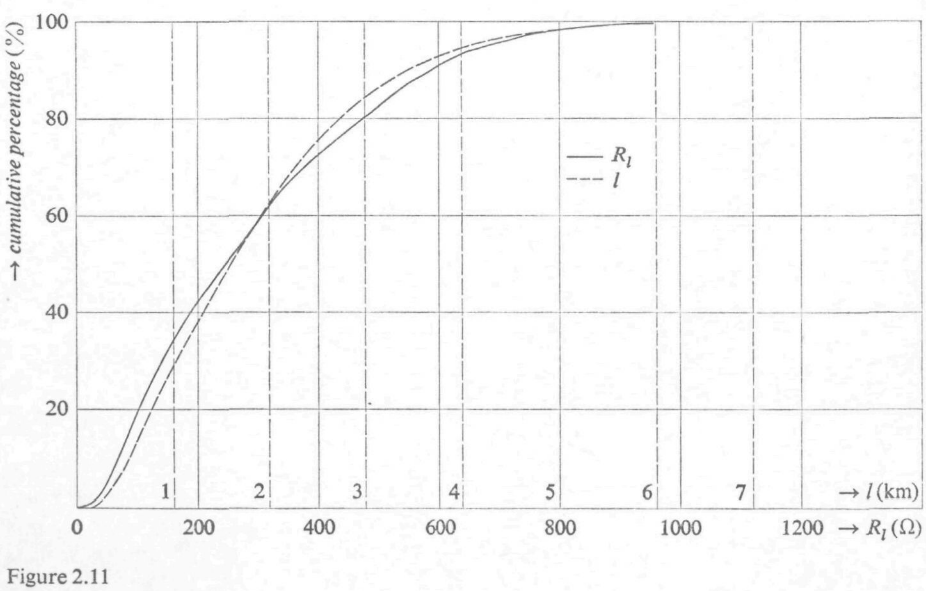


Figure 2.11

The mean value and standard deviation were calculated:

$m_{R_l} = 295.2\,\Omega\,(95\,\%$ confidence limits $\pm\, 11.1\,\Omega)$

$s_{R_l} = 213.7\,\Omega$

Although the distribution has roughly the same shape as the distribution of length (dotted curve in Figure 2.11), there are obvious differences. In the middle part (20–80 %) the curve is less steep and for lower and higher values it has a greater slope. So, it is clear that there is no linear relationship between loop resistance and length. This is also indicated by the correlation coefficient which was calculated:

$$r_{l.R_l} = \frac{s_{l.R_l}}{s_l . s_{R_l}} = 0.887$$

This value indicates a moderate degree of correlation, but not at all a completely linear relationship.

In studying this effect, we should be aware of the fact that over the years in local networks cable conductors of various diameter have been used. Up to about 1950 mainly conductors with diameters of 0.8 and 0.6 mm were applied. Since 1949 0.5 mm conductors have also been used, at first only under specific restrictions, but later on more generally. A few years later even 0.4 mm conductors were introduced, but to a limited extent. The period of 1958-1964 was characterized by a gradual standardization of cables for local networks. For subscribers' lines almost exclusively 0.5 mm conductors are applied; only for exceptionally long lines 0.8 mm cables are used.

In order to analyse the effect of these different conductor gauges on the results of the

Table 2.3

Length	Number of lines	Resistance per km Mean	Stand. dev.
0 –0.5 km	162	142.3 Ω/km	41.0 Ω/km
0.6–1.0	284	144.7	38.7
1.1–1.5	236	163.1	48.2
1.6–2.0	228	161.7	45.4
2.1–2.5	183	170.0	43.6
2.6–3.0	125	166.9	39.1
3.1–3.5	81	167.9	41.2
3.6–4.0	56	162.5	29.4
4.1–5.0	48	149.5	29.1
$\geqslant 5.1$	30	137.0	31.8
Overall	1433	157.3	48.3

survey, the resistance per kilometre was calculated for each subscriber in the survey. For classes of length the mean value and the standard deviation are given in Table 2.3. Considering these results we should take into account that rounded values were used in the raw data. This will influence the standard deviation of the calculated resistance per kilometre, especially for the groups with smaller lengths.

From Table 2.3 we can conclude that for lines shorter than 1 km and those longer than 4 km, the resistance per km is distinctly smaller than for lengths in between. This explains the difference in shape between the cumulative distributions of length and resistance (see Figure 2.11). An explanation for the lower resistance of long lines can probably be found in the planning rules, which limit the loop resistance of a subscriber's line to 1000 Ω. Thus 0.4 mm conductors can only be used for lengths up to 3.6 km (see Table 2.4 which contains the resistance per kilometre for conductors most frequently found in the networks). It is for this reason, and also in view of the attenuation, that, if subscribers' lines of greater length are to be installed, conductors of larger diameter are preferred for these lines.

Table 2.4

Conductor-diameter	Resistance per kilometre
0.4 mm	275 Ω/km
0.5	174
0.6	120
0.8	68

The low resistance found for short lines can perhaps be explained from the fact that in the past use was made of conductors with a larger diameter than in the later network extensions, often at greater distance from the local exchange. So short lines relatively frequently contain older, heavy-gauge conductors.

Comparison of the overall mean value of 157.3 Ω/km (Table 2.3) with the values in Table 2.4, shows that when the survey was made there was still a considerable number of lines with a conductor diameter exceeding 0.5 mm. A better insight can be obtained by studying the distribution of calculated values of the resistance per kilometre for several groups of length (see Figure 2.12). In the overall distribution (Figure 2.12a) we find a clear indication that 0.5 mm conductors (174 Ω/km) are often used. To a smaller extent this also applies to 0.6 mm conductors (120 Ω/km). Apparently lines only containing 0.8 and 0.4 mm conductors are rather seldom. Figure 2.12a also indicates that many lines are composed of parts with different conductor gauges. In such cases the resulting resistance per kilometre will have a value in between those of Table 2.4.

In Figure 2.12b (short lines) we find a concentration around the values corresponding with 0.5 and 0.6 mm. With these short lines we should be aware of the effect of rounding

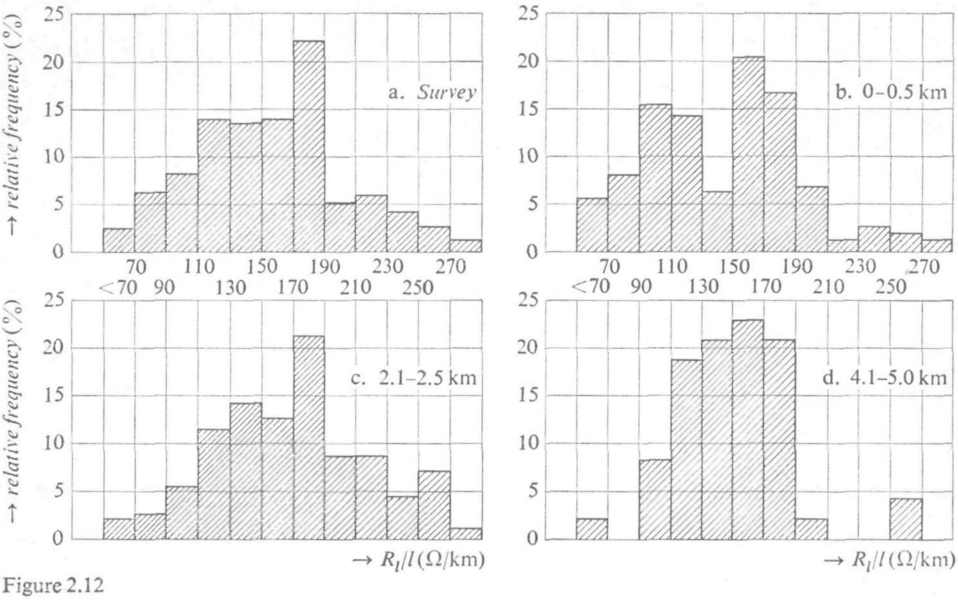


Figure 2.12

the data concerning length and resistance. Apparently the proportion of 0.4 mm conductors is smaller, whereas larger diameters are more frequently represented than in the complete sample. This is in agreement with the explanation given above.

The histogram for lines of average length (2.1-2.5 km, see Figure 2.12c) shows no remarkable difference with the overall results.

In a group of lines of greater length (4.1-5.0 km, see Figure 2.12d) conductors smaller than 0.5 mm are rare. We can assume that a large proportion of lines will contain 0.5 or 0.6 mm conductors or a combination of both.

Next we can consider the resistances found in the networks of Rotterdam and The Hague together. For the mean value and standard deviation we find:

$$m'_{R_l} = 259.2\,\Omega \text{ (95\% confidence limits } \pm 20.8\,\Omega)$$

$$s'_{R_l} = 180.8\,\Omega$$

These values differ significantly from those of the complete survey. The reason is that the resistance per kilometre deviates considerably; for Rotterdam and The Hague the mean value is 140.3 Ω/km. The histogram in Figure 2.13 gives the frequency distribution of the resistance per kilometre, which shows great resemblance to the results of short lines in the complete sample (Figure 2.12b). Obviously in 1966 there was still a considerable proportion of older cables in these two cities.

Assuming that the Amsterdam network would show similar results, we can estimate the effect of this network being not included in the survey. The mean value of loop resistance in Amsterdam would differ roughly 10% from the sample mean, as was the

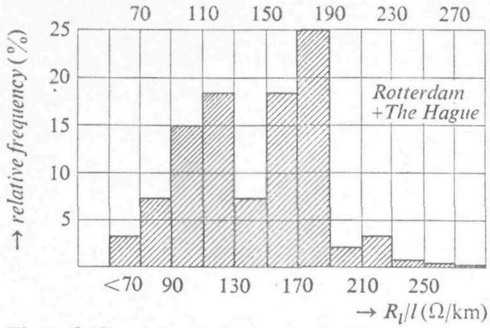


Figure 2.13

case in Rotterdam and The Hague. Since the Amsterdam network contained some 10% of all subscribers in the national network, we can estimate that the resulting difference between the sample mean and the population mean can be in the order of 1%. This value is well within the confidence limits of the sample mean. We can, moreover, expect that in the course of years the resistance will change as a result of standardization on 0.5 mm conductors (see Paragraph 2.8.2).

2.6 *Relation between number of metering pulses and line length*

As already mentioned in Section 2.2, for each subscriber information was collected in the survey on the number of metering pulses during the preceding year. The number of metering pulses is more or less a measure for the outgoing telephone traffic originating from the subscriber, but a distinction into call categories (local, trunk, international) is impossible. And, of course, the number of metering pulses does not give any direct information on the incoming traffic, although it seems reasonable to expect that there is a positive correlation between incoming and outgoing telephone traffic. The results of the survey were only available in the form of a two-way classification table with the variables length and number of metering pulses, directly taken from the raw data. After pooling some groups in order to obtain sufficiently high frequencies in all cells, we found the results presented in Table 2.5. It is evident from the total that the information wanted was not available about all subscribers, but this is not expected to have a systematical influence.

We pose the hypothesis that there is no systematic relation between number of metering pulses and length, and check this by means of a chi-square test. The result shows that there is no significant deviation from our hypothesis, because, owing to random variations, the probability of exceeding the calculated chi-square value is 27%. This result supports the assumption, of which use is made in this treatise, that telephone traffic on subscribers' lines is independent of line length.

Table 2.5

Number of pulses	Number of lines with length 0–0.5	0.6–1.0	1.1–1.5	1.6–2.0	2.1–2.5	2.6–3.0	3.1–4.0	>4 km	Total
0–1000	25	41	35	36	31	20	17	13	218
1001–2000	31	75	53	53	35	40	41	18	346
2001–3000	20	46	43	45	26	22	27	20	249
3001–4000	11	29	30	24	19	9	14	12	148
4001–6000	24	31	31	20	29	15	13	10	173
6001–10000	27	23	21	23	15	12	13	6	140
> 10000	22	34	21	21	19	6	12	8	143
Total	160	279	234	222	174	124	137	87	1417

2.7 *Approximations*

2.7.1 *Distribution of length*

For calculations on the characteristics of subscribers' lines it would be very convenient if the distribution of length could be represented by a simple formula. Figure 2.3 already indicated that an approximation by a Gaussian distribution is not suitable. So we look for another distribution function which offers a sufficiently accurate approximation, and which should preferably be represented by a simple mathematical form enabling such operations as integration and calculation of moments easily to be performed.

A distribution which has a shape very similar to the distribution function of length and which can be found in many tables, is the 'chi-square distribution', and in particular the one with four degrees of freedom. Chi-square distributions are related to the sum of the squares of a number of independent random variables each of which is distributed normally. The number of degrees of freedom refers to the number of variables. In spite of this rather complicated definition the formulas describing the distribution are simple, in particular those for the distribution with four degrees of freedom. In that case the probability density function (in standardized form) is given by:

$$f(x) = \frac{1}{4} x \, e^{-\frac{x}{2}} \quad \text{for } x \geqq 0, \text{ and } f(x) = 0 \text{ for } x < 0 \tag{2–4}$$

The cumulative distribution function is:

$$F(x) = \int_0^x \frac{1}{4} u \, e^{-\frac{u}{2}} \, du = 1 - e^{-\frac{x}{2}} \left(1 + \frac{x}{2}\right) \tag{2–5}$$

If we substitute a new variable l in such a way that $x = 2\,a\,l$, the distribution function of l becomes:

$$F(l) = 1 - e^{-a\,l}(1 + a\,l) \tag{2-6}$$

and consequently the probability density function:

$$f(l) = a^2\,l\,\mathrm{e}^{-a\,l} \tag{2-7}$$

Now we can calculate the mean and standard deviation:

$$\mu_l = \int_0^\infty l\,a^2\,l\,\mathrm{e}^{-a\,l}\,\mathrm{d}l = \frac{2}{a} \quad \text{and}$$

$$\sigma_l^{\,2} = \int_0^\infty l^2 a^2\,l\,\mathrm{e}^{-a\,l}\,\mathrm{d}l - \mu_l^{\,2} = \frac{2}{a^2}, \text{ so } \sigma_l = \frac{\sqrt{2}}{a}$$

Similar approximations have been indicated by Kremer and Kitchenn for the distribution of radial distance. Kremer [15] assumed a subscriber density (i.e. number of subscribers per square km) which decreases exponentially with radial distance. This results in a chi-square distribution with four degrees of freedom for the radial distance. Kremer compared this result with the distribution found in the United Kingdom (see Paragraph 2.4.4) and he concluded that there is a very good agreement. Kitchenn [6] found a substantially linear relationship between the logarithm of the subscriber density and the radial distance for rural subscribers. From this a probability density function for radial distance similar to formula (2–7) can be deduced.

Next we wish to find that value of a in formulas (2–6) and (2–7) giving results which fit in best with the distribution of length in the survey. For this purpose several well-known methods are available [3, 4], the most common being the method of 'least square curve fitting' [4]. We can determine the value of a which minimizes the sum of the squares of the differences between expected and observed frequencies. The value found is $a = 1.066$/km.

For our purposes this method of curve fitting does not seem the most suitable. It is more in accordance with the statistical importance of deviations in frequency to relate these deviations to expected frequencies. This feature is offered by the 'chi-square method' as it is called, which also enables a simple test on the significance of the deviations [4]. For this purpose we pooled some classes of length in order to obtain sufficiently high frequencies (see Table 2.6). For a minimum value of χ^2 we find:

$a = 1.083$/km and $\chi^2 = 51.3$.

From this value of a it follows that $\mu_l = 1.847$ km and $\sigma_l = 1.306$ km. The significance of the deviations can be tested by calculating the probability of exceeding the value 51.3 in a chi-square distribution with 41 (number of classes minus 2) degrees of freedom. This probability is 13.1 % and we can conclude that there is a reasonable chance

Table 2.6

Length (km)	Observed frequency	Expected frequency	Contribution to χ^2	Length (km)	Observed frequency	Expected frequency	Contribution to χ^2
0–0.2	20	43.9	13.0	2.4	28	30.0	0.1
0.3	36	36.3	0.0	2.5	37	28.0	2.9
0.4	49	43.5	0.7	2.6	25	26.2	0.1
0.5	57	48.8	1.4	2.7	23	24.4	0.1
0.6	56	52.6	0.2	2.8	26	22.7	0.5
0.7	65	55.1	1.8	2.9	26	21.1	1.1
0.8	49	56.5	1.0	3.0	25	19.6	1.5
0.9	58	57.0	0.0	3.1	15	18.2	0.6
1.0	56	56.9	0.0	3.2	22	16.8	1.6
1.1	46	56.2	1.8	3.3	16	15.6	0.0
1.2	48	55.0	0.9	3.4	19	14.4	1.5
1.3	54	53.4	0.0	3.5	9	13.3	1.4
1.4	43	51.7	1.5	3.6	10	12.3	0.4
1.5	45	49.7	0.4	3.7–3.8	29	21.7	2.4
1.6	49	47.5	0.0	3.9–4.0	17	18.4	0.1
1.7	52	45.3	1.0	4.1–4.2	13	15.6	0.4
1.8	47	43.1	0.4	4.3–4.5	20	19.0	0.1
1.9	42	40.8	0.0	4.6–4.8	12	14.6	0.5
2.0	38	38.5	0.0	4.9–5.4	13	19.9	2.4
2.1	43	36.3	1.2	5.5–6.0	9	11.6	0.6
2.2	48	34.1	5.6	$\geqslant 6.1$	11	15.4	1.3
2.3	27	32.0	0.8	total	1433	1433	51.3

that the proposed approximation indeed represents the distribution of length in the population. In Figure 2.14 the approximation is shown next to the survey results, whereas in Table 2.6 the corresponding frequencies (column 'expected frequency') are given. The calculated contributions to chi-square for each cell, as indicated in Table 2.6, show that the group of shortest lines contributes to a considerable extent. This reminds us of the fact already observed in Section 2.3 that the survey only contained a small number of very short lines. In Paragraph 2.4.2 a similar tendency was indicated. This could imply that a chi-square distribution, shifted by a certain length (b), might give an even better approximation.

The general formulas for such a distribution are:

$$f(l) = a^2(l-b)\,e^{-a(l-b)} \text{ for } l \geqq b \text{ and } f(l) = 0 \text{ for } l < b$$

$$F(l) = 1 - e^{-a(l-b)}\{1 + a(l-b)\}$$

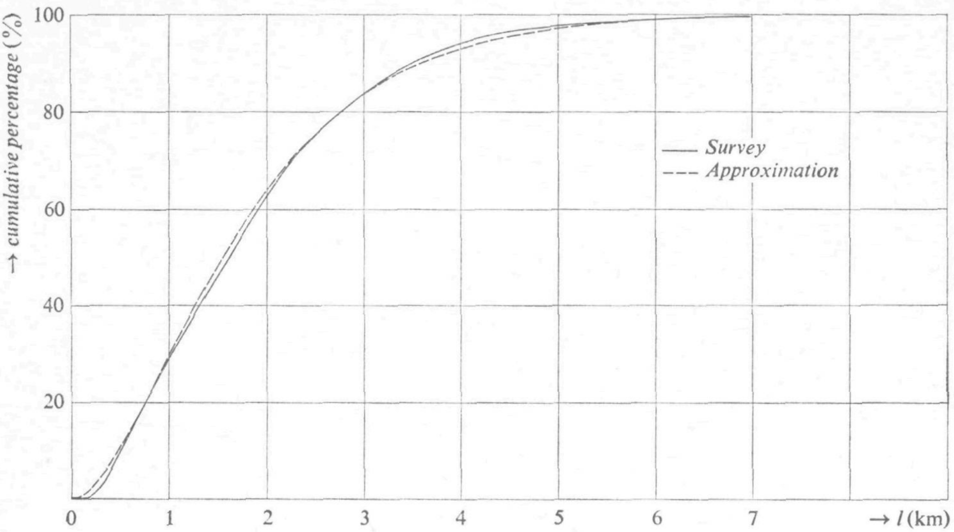


Figure 2.14

The best values for a and b are found by minimizing the value of χ^2: $a = 1.130$/km, $b = 0.079$ km and $\chi^2 = 39.7$.
The values for mean and standard deviation are

$$\mu_l = \frac{2}{a} + b = 1.849 \text{ km and } \sigma_l = \frac{\sqrt{2}}{a} = 1.252 \text{ km}$$

The probability of exceeding a value of 39.7 for χ^2 is 48.5%. Thus the approximation is a good one; the deviations found in the survey can very well be explained by random variations due to random sampling.
For practical applications often an approximation given by formula (2–6) and with a rounded value for a ($a = 1.1$/km) will be sufficiently accurate. In that case the value of χ^2 (51.9) is only slightly higher than the minimum found for formula (2–6), and the approximation is hardly less likely than the one corresponding to the optimum value of a.

With $a = 1.1$/km, we find $\mu_l = 1.818$ km, $\sigma_l = 1.286$ km (2–8)

2.7.2 *Distribution of loop resistance*

Now we will try to find an approximation for the distribution of loop resistance found in the survey. Comparison of Figure 2.11 and Figure 2.14 shows that the distribution of loop resistance, too, has a shape more or less similar to a chi-square distribution with four degrees of freedom, although a less well fitting can be expected. To find the best result we applied the 'chi-square method' to a table containing 62 classes. Then the probability density function of the optimum approximation is:

$f(R_l) = 0.00677^2\, R_l\, e^{-0.00677\, R_l}$

The corresponding values for mean and standard deviation are:

$\mu_{R_l} = 295.2\,\Omega$ and $\sigma_{R_l} = 208.9\,\Omega$

The chi-square test shows a highly significant deviation. This means that the approximation cannot be expected to represent exactly the distribution of the population from which the survey is a random sample. On the other hand Figure 2.15 shows that the curves for the survey results and the approximation are rather close together, at least sufficiently close for many practical applications.

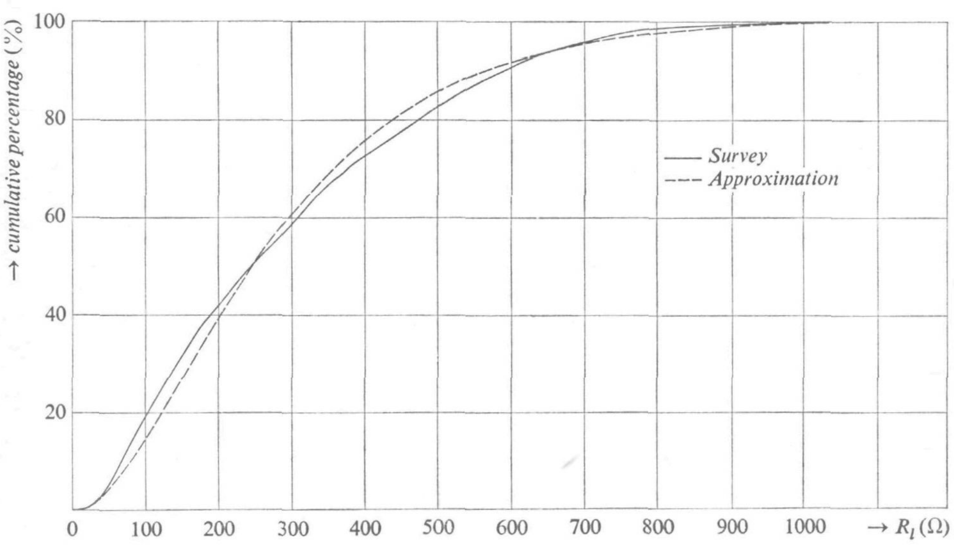


Figure 2.15

2.8 *Validity of survey results in the long run*

The survey represents the situation in local networks in the year 1966. It is important to have an idea to what extent the results can also be considered representative of the situation in later years. For that purpose it is useful to consider a number of factors which can influence the statistical properties of subscribers' lines.

These factors can be divided into two groups: one related to effects of growth and expansion and the other connected with changes in the technical structure of the subscriber's line plant. We will shortly discuss a number of these factors.

2.8.1 *Growth and expansion*

a *Increasing subscriber density*

In 1966 there were about 13 subscribers per 100 inhabitants in the Netherlands. In 1973 this number had increased to 21 per 100. In the same period the number of subscribers per 100 houses increased from 48 to 67. Such a growth in itself will only change the total number of subscribers' lines, but not the distribution of length, as long as other factors, such as the geographical distribution of houses and the structure of the networks are not changed.

b Increasing number of inhabitants

From 1966 to 1973 the number of inhabitants in the Netherlands has grown from about 12.5 to 13.5 million, and the population is still growing. The number of the houses increased from 3.4 to 4.2 million. This resulted in a growth of existing towns and villages. Sometimes small villages expanded into important suburbs. Generally the extensions will be located outside the old centres where the local telephone exchange was usually situated. This suggests a tendency towards longer subscribers' lines, but this will be compensated for, at least to some extent, by the following effect.

c *Increasing number of local exchanges*

The growing number of subscribers and the extension of densily populated areas led to the construction of new exchanges, including local exchanges in municipal areas. In 1966 the number of local exchanges in the Netherlands was 1241 and at the end of 1973 it had increased to 1295. In this period the area of land had also been increased by reclaiming another part of the former Zuider Zee, but this increase was only 1.3% and up till now very few people have been living in this new polder. So, the average exchange area is decreasing, and in principle some reduction of the percentage of long subscribers' lines can be expected.

2.8.2 *Technical changes*

a *Changes in cables*

The detailed structure of the subscriber's line plant over the years has changed gradually and is still changing. For a long time a system with main and distribution cables was used, the latter cable often in the form of a 'ring cable'. Subscriber connecting cables are jointed direct to the distribution cable. There is generally not more than one cross-connection point between exchange and subscriber. In the past many types of cable and several conductor gauges were used in this network. In the years around 1960 standardization of 0.5 mm conductors was realized (see Section 2.5). Consequently, extensions and renewals in the network will lead to a diminishing importance of non-standard conductors; in the long run their influence will become negligible. These changes will influence the distribution of loop resistance. At present polyethyleen insulated cables are gradually being introduced instead of the usual paper insulated types. The new types of cable (with 0.5 mm conductors) can have a somewhat higher mutual capacitance. For the coming years the resulting effect is expected to be sufficiently taken into account by the average value of 35 nF/km (see Section 2.9).

b *Introduction of the 'pre-wiring system 58'*

In 1958 a system of 'pre-wiring during the construction of houses' was introduced. In each house a cable containing two pairs for telephone facilities and four pairs for the wire-broadcast service was installed [18, 19, 20]. The system usually contains two cross-connection points between exchange and subscriber. This may lead to a slight increase in the length of subscribers' lines compared with the older system. In the '58-system' only 0.5 m conductors are used. At the time of the survey about 15% of the subscribers was equipped with this system.

c *Introduction of the 'pre-wiring system 68'*

In 1968 a new system of pre-wiring was introduced. It no longer contains pairs for wire-broadcasting as a result of a Government decision to discontinue this service. The capacity of this system is such that it can serve all houses with two subscribers' lines; in the '58-system' this was only possible for some 10% of the houses. The '68-system' is equipped with one cross-connection point in the subscriber's line [21].

2.8.3 *Overall effect of changes*

In addition to the effects referred to in 2.8.1 and 2.8.2 the statistics of subscribers' lines can, of course, be influenced by many other factors especially in the social field, e.g. changes in people's attitude with regard to accommodation facilities, living in the country, having a second house for the weekends, etc. Also developments in the economic field, e.g. foundation of new industries, new offices, shopping centres, etc. can have an impact on the subscriber's line plant.

As long as the existing planning rules for the telephone network are not being changed drastically, we can estimate that the effect on the distribution of subscriber's line length, resulting from all the technical and non-technical impacts mentioned in this section, will be relatively small. Moreover, some effects are to a certain extent opposite. So we can expect that the distribution of length will only change very slowly. This conclusion is supported by a similar one formulated by Gresh (see Paragraph 2.4.3) after comparison of the results of two surveys with an interval of four years. A same effect has been described in Paragraph 2.4.4, i.e. over a period of four years no appreciable difference could be detected in the distribution of radial distance in the United Kingdom.

As far as cable parameters are concerned, those of 0.5 mm conductors will become more and more predominant, as a result of both growth (the number of subscribers doubled in about 9 years) and renovation.

2.9 *Model network*

For practical applications it is useful to derive a model of the average subscriber's line plant from the survey results. For our purpose statistical distributions are relevant and not absolute numbers of subscribers.

As far as the distribution of length is concerned a chi-square distribution with four degrees of freedom and with $a = 1.1$/km (see Paragraph 2.7.1) offers a reasonable representation of the real situation.

Concerning the electrical characteristics of subscribers' lines, we note that, with regard to telephony, loop resistance is an important parameter. In view of the validity for calculations on the present and future transmission performance of subscribers' lines, it is advisable to base our model on the universal application of 0.5 mm conductors. From the other primary cable parameters, for the frequencies involved, we can neglect the effect of leak resistance, whereas for all types of cable used in the Netherlands subscriber's line plant the values for mutual inductance and capacitance per kilometre are roughly the same. So, with sufficient accuracy, we can take average values for the two last-mentioned parameters.

Concerning the distribution of telephone traffic in our model, we can assume that there is no relation between the amount of traffic on a subscriber's line and the length of this line. So, the telephone traffic will be equally distributed over all lines.

Thus the characteristics of our model network are as follows:

- distribution of length described by:

$$\begin{aligned} f(l) &= 1.21\, l\, e^{-1.1l} \quad (l \text{ in km}) \\ F(l) &= 1 - e^{-1.1l}(1 + 1.1l) \end{aligned} \qquad (2\text{–}9)$$

- electrical characteristics: $R = 174$ Ω/km, $L = 0.7$ mH/km, $C = 35$ nF/km, leak resistance negligible.
- telephone traffic: equally distributed over all lines.

2.10 *New survey in the future*

The growth in the telephone network makes it desirable to envisage the possibility of a new survey, say some 10 to 15 years after the present survey. In this connection it is a favourable circumstance that the Netherlands PTT meanwhile started an Integral Subscriber Information System [22], in which a series of data concerning all subscribers is stored in a computer memory. It is planned that technical information on the subscribers' lines will be incorporated in this system. For the conversion of the existing technical records and the implementation of the system a period of several years will be required (planning extents to 1980 [22]). Nevertheless, it seems advisable to wait with a new survey until this system is operational. It would offer an almost ideal opportunity of drawing an extensive sample and collecting much more detailed information than was possible in the present survey.

References Chapter 2

1 Bakker, C., *Statistical survey of length, loop resistance and attenuation of subscribers' lines in the Netherlands.* In: Het PTT-Bedrijf, XVI no. 4 (1970), pp. 203-211.
2 CCITT, *Red Book*, Vol. Vbis, pp. 106-108 (ITU, Geneva, 1965).
3 Cramér, H., *Mathematical methods of statistics* (Princeton University Press, 1951).
4 Spiegel, M. P., *Theory and problems of statistics* (McGraw-Hill Book Cy, New York, 1961).
5 Zijp, W. L., *Handleiding voor statistische toetsen* (Tjeenk Willink, Groningen, 1974).
6 Kitchenn, R. G., *A transmission survey of subscribers' telephone services.* In: The Journal of the Institution of Engineers, Australia, 40 no. 9 (1968), pp. 195-209.
7 Kremer, H., *Ortsnetzplanung*, p. 68 (Schiele & Schön, Berlin, 1963).
8 Hinderliter, R. G., *Transmission characteristics of Bell System subscriber loop plant.* In: IEEE Transactions Communication and Electronics, Vol. 82 (1963), pp. 464-470.
9 Gresh, P. A., *Physical and transmission characteristics of customer loop plant.* In: The Bell System Technical Journal, 48 no. 10 (1969), pp. 3337-3385.
10 Davis, C. H., *A survey of customer loops in the General System.* In: Automatic Electric Technical Journal, 12 no. 4 (1970), pp. 150-159.
11 Davis, C. H. and Lally, W. J., *Systems engineering survey of subscriber loop plant.* In: IEEE Transactions on Communication Technology, Vol. Com-19 no. 1 (1971), pp. 71-79.
12 Goldsmith, J. R. and Hewstone, H. D., *Exchange-line costing study.* In: The Post Office Electrical Engineers' Journal, 56 no. 3 (1963), pp. 186-192.
13 Richards, D. L., *Telecommunication by speech*, p. 497 (Butterworths, London, 1973).
14 Sattelberg, O., *Aufbau und Planung von Ortskabelnetze.* In: Der Fernmelde-Ingenieur, 9 no. 10 (1956), pp. 1-39.
15 Kremer, H., *Verteilung der Luftlinienentfernungen von Fernsprechanschlüssen.* In: Fernmelde-Praxis, 41 no. 8 (1964), pp. 310-312.
16 Dehmer, S. and Wirz, H., *Contribution of the Federal Republic of Germany.* In: International Seminar on National Telephone Transmission Planning, Melbourne 1970, Vol. 1, Seminar papers, pp. 3.1-3.18.
17 Angrick, W., *Über den Ausbau und die Struktur der Fernsprech-Ortsnetze bei der Deutschen Bundespost.* In: Jahrbuch des elektrischen Fernmeldewesens, 13, pp. 352-385, Bad Windsheim, 1962.
18 Verhage, G., *Etablissement lors de la construction d'habitations de raccordements standardisés au réseau téléphonique.* In: Revue FITCE, 2 no. 6 (1963), pp. 31-37.
19 Schreuder, W. P. H., *Lokale telefoonnetten.* In: Het PTT-Bedrijf, XIV no. 4 (1966), pp. 149-157.

20 Hendriks, H. A., *De ontwikkeling van de verbindingswegen in het Nederlandse telefoonnet*. In: Het PTT-Bedrijf, XI no. 3/4 (1962), pp. 160-186.
21 Hendriks, H. A., *Aanleg van telefoonleidingen in de nieuwbouw*. In: Data, 71 no. 1-2 (1970), pp. 25-35.
22 Alkhoven, G. and Wage, J., *ITCIS, Integraal Telefoon-Cliënten Informatie Systeem*. In: Het PTT-Bedrijf, XVIII no. 3 (1973), pp. 151-159.

3 Distribution of reference equivalent of subscribers' lines

3.1 *Introduction*

As stated in Section 1.4, 'reference equivalent' (RE) relates to a principal variable in transmission planning, i.e. loudness loss. The RE of a subscriber's line can be defined as the increase of the RE of the subscriber's local system, caused by the insertion of the line. This description used by the CCITT [1] assumes the same value for the sending and the receiving direction. Here the fundamental problem of the additivity of RE, referred to in Section 1.4, crops up. The characteristics of the other parts of the complete speech path determine to what extent the insertion of the subscriber's line will influence the loudness of speech received. For example: if the telephone receiver at the receiving end shows a frequency response with a sharp cut-off at, let us say, 2800 Hz, it is clear that the insertion loss of the subscriber's line at frequencies higher than 2800 Hz will have no influence on the RE. In this respect not only the characteristics of the telephone sets are important, but also those of other circuits included in the transmission path.

So, in principle, the influence of the subscriber's line on loudness depends on the characteristics of the complete connection, which will vary with different calls. However, in order to reduce our considerations to an acceptable level of complexity and to be able to study the influence of the subscribers' lines on loudness separately, we need an unambiguous value for the RE of these lines. For this purpose we shall have to standardize more or less arbitrary characteristics of some reference connection into which the subscriber's line will be assumed to be inserted.

We also shall have to determine the relationship between the line RE, which is basically a subjectively determined value, and the objective transmission characteristics of the subscriber's line. Using the distribution of length, we next can arrive at the distribution of line RE.

There is another effect brought about by the insertion of a subscriber's line which deserves attention, namely the influence of the loop resistance on the sensitivity of the carbon microphone, as indicated in Section 1.3. The feeding current of the microphone is usually supplied from a feeding bridge in the local exchange; a simplified circuit diagram of such a feeding bridge is given in the left hand part of Figure 3.1. For the study of the d.c. properties the feeding system can be represented by a battery with a voltage V_b and a series resistance R_b; the loop resistance R_l represents the subscriber's line.

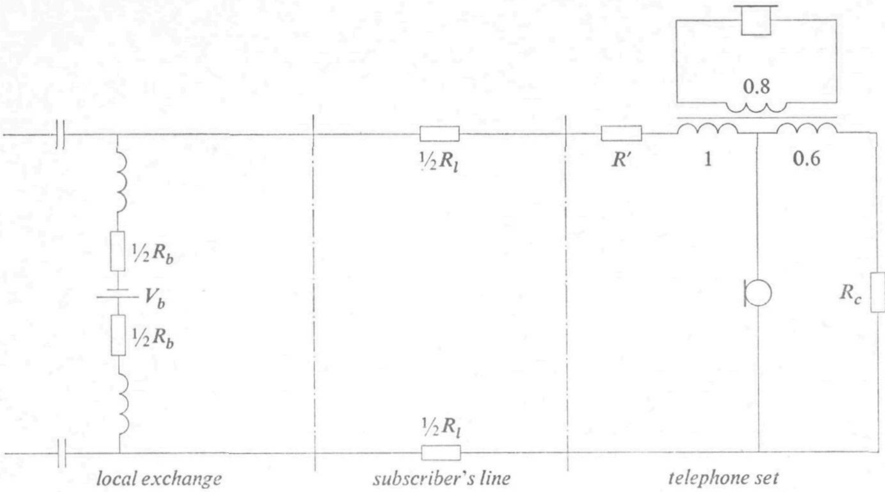


Figure 3.1

The decrease in sensitivity of the carbon microphone (expressed in transmission units) brought about by the insertion of R_l is known as 'feeding loss'. This feeding loss will influence the sending RE of the local system. So, in the study of the influence of the subscriber's line on the RE, in the sending direction, the feeding loss should be added to the transmission loss of the line.

A simplified circuit diagram of the standard transmission circuit in the Netherlands telephone sets [2] is given in the right-hand part of Figure 3.1. For d.c. the (carbon) microphone is shunted by the balance resistor R_c. Consequently the value of R_c will influence the extent to which the sensitivity of the microphone is changed by the insertion of R_l. The feeding system, the transmission circuit and the balancing network inside the telephone sets, as well as the type of carbon microphone used, may vary considerably amongst national networks. It is therefore unlikely that a rule of thumb based on a linear relationship between feeding loss and loop resistance which has found more or less general application [3, 4, 5] is suitable in all cases.

In the Netherlands the presence of two different feeding systems makes matters even more complicated. Which system is used depends on the type of the local exchange. Nominal values of these systems are: $V_b = 48$ V, $R_b = 800\ \Omega$ and $V_b = 60$ V, $R_b = 1000\ \Omega$ respectively.

The foregoing emphasizes the desirability to investigate the behaviour of the carbon microphone under various feeding conditions, for the purpose of finding a relationship between the sensitivity of the microphone and loop resistance. This relationship will enable us to ascertain the total effect of the insertion of a subscriber's line, on the sending RE. So ultimately we can determine the statistical distribution of the RE of subscribers' lines for the sending direction.

Moreover, we shall consider the influence of variations in the feeding system on feeding loss and their contribution to the spread of the sending RE.

3.2 *Method for the calculation of the RE of subscribers' lines*

The CCITT has published a rule of thumb for the value of the RE of a subscriber's line, based on the experience of many countries [6]. According to this rule the line RE is equal to the image attenuation at 800 Hz, multiplied by a factor K. K is independent of length but slightly dependent on the conductor diameter; for the usual conductors the value of K is close to one.

It is obvious that this rule can only give a rough approximation of the values occurring in practice, because its basis is image attenuation instead of insertion loss; hence the influence of differences in terminating impedances is not taken into account.

Apparently, this rule of thumb is based on average conditions. This should be realized when considering the Dutch situation, the nominal impedance of the telephone network being 800 Ω (see Section 5.1), whereas internationally 600 Ω is usual; in the NOSFER 600 Ω is used as well. Based on measurements of the difference in insertion loss of subscribers' lines terminated at the exchange end by 600 Ω and 800 Ω successively, we adapted the CCITT-rule to the Dutch situation. In calculations used in transmission planning this resulted into a rule of thumb that the RE amounts to

$$0.93 \text{ dB/km for } 0.5 \text{ mm cable.} \qquad (3-1)$$

This rule could hardly be verified because of the absence of a sufficient number of straightforwardly determined values of RE of real or artificial lines. So the rule represented by formula (3 – 1) can only be considered as a first approximation and it seems highly desirable to find a more satisfactory method for the calculation of the RE of subscribers' lines.

In the CCITT Handbook *Local Telephone Networks* [7], too, a more elaborate method is given for the calculation of the RE of a subscriber's line.* It is presented as a graphical method in which the insertion loss corresponding to the actual terminating conditions is plotted in a diagram with a logarithmic frequency scale and a linear dB attenuation scale. The mean value of insertion loss in the frequency band 200-4000 Hz is determined and used as an approximation of the value of the line RE. It seems that this second method is applicable on a larger scale, because it is based on insertion loss. Another feature is that averaging is performed on a logarithmic frequency scale. But a frequency range extending from 200 to 4000 Hz seems unrealistic as compared with the much more limited frequency band effectively transmitted in other parts of a com-

* The various methods published in the CCITT Handbook are intended to give some guidance, they should not be considered recommendations.

plete telephone connection. Moreover, it is not evident that the mean value of insertion loss, on a dB-scale, is an adequate measure for the effect on loudness. This aspect is worth some closer consideration.

The physiological background of loudness has gradually become understood. Recent publications of different authors [8, 9, 10] dealing with this subject show a reasonable agreement. These authors also consider the possibility of determining RE by objective measurements; the crucial point is how to measure loudness. Several decades ago already Braun studied this problem [11, 12] and he developed the well-known OBDM (Objectiver Bezugsdämpfungs Messer = Objective Reference Equivalent Meter, OREM). Although nowadays some parts of the complete measuring set-up, such as the artificial mouth and ear, are considered insufficiently representative of real conditions, the basic principle does not differ much from the ideas expressed in more recent publications.

The objective measuring method has several features, based on empirical findings, which are particularly relevant to our purpose. The first is that the contribution of different parts of the frequency band to loudness is inversely proportional to frequency. This means that on a logarithmic frequency scale the weighting over the frequency band becomes flat. Another important feature of the objective method is that the contribution of different spectral components to loudness appeared to be proportional to about the fourth power root of the sound intensity in the ear. Conversion, via sound pressure, into signal voltages within the electrical part of the speech link, results in contributions to loudness proportional to the square root of the voltage. Therefore, the conclusion is that loudness is approximately proportional to the mean value of the square root of voltage, averaged on a logarithmic frequency scale.

In Section 3.1 mention was made of the influence of the characteristics of other parts included in the complete speech link, and the need to establish the characteristics of a standard connection which can be used in our calculations. To arrive at such a standard connection, the following considerations may be useful.

In practice, the value of the overall RE usually becomes more critical in longer and more complicated connections. In these connections we can expect a rather sharp limiting of the frequency band transmitted. Loaded cables, telephone exchanges, channel terminal equipment for carrier systems, hybrid transformers, etc., will more or less rigorously limit the frequency band transmitted. So, outside the nominal transmission band 300-3400 Hz there is as a rule considerable attenuation. And also inside this band there will be attenuation/frequency distortion, showing for many components the systematic tendency to introduce additional loss at one or both extremities of the band. Moreover, most transmitters in modern telephone sets have a falling sensitivity at lower frequencies in order to suppress the sidetone effect of room noise. Usually the effective frequency band of telephone receivers is limited as well, for instance, the receivers used at present in the Netherlands show a rather sharp cut-off slightly below 3400 Hz.

Taking into account these effects and bearing in mind the limits specified in CCITT recommendations for the attenuation/frequency characteristics of a chain of circuits, channel terminal equipment, international exchanges, etc. it seems justified to limit the frequency band that will be of importance with regard to the influence of subscribers' lines on loudness, to frequencies between 400 and 3000 Hz. Within this band a flat attenuation characteristic will reasonably represent the overall response of real complete speech links, the subscriber's line under consideration excluded.

With the help of the relationship found in the above, the line RE* can easily be derived from the insertion loss. In fact we have to convert insertion loss into a voltage ratio and to determine the mean value of the square root of this ratio in the frequency band 400-3000 Hz, using a logarithmic frequency scale. For the purpose of our calculations we simplify integration over the frequency band by dividing the band into six sub-bands each with a width of a factor 1.4 ($\approx$ half an octave). We assume the insertion loss at the frequency in the middle (on a logarithmic scale) of each of these sub-bands as being representative of the sub-band concerned. Such a simplification is justified as long as the attenuation/frequency characteristic is rather smooth, which is the case for subscribers' lines. The six sub-bands and the midband frequencies used in our calculations are listed in Table 3.1.

Table 3.1

Sub-bands	Midband frequency
400– 560 Hz	473 Hz
560– 784	663
784–1098	928
1098–1537	1299
1537–2151	1818
2151–3012	2545

3.3 *Properties of carbon microphones*

Not much progress has been made so far with the study of theoretical and practical aspects of carbon microphones, although some articles on this subject have meanwhile been published [13, 14, 15], however showing diverging conclusions. This is not astonishing taking into account that many factors will influence the behaviour of the microphone, e.g. form, size, surface, resistance and weight of the carbon granules; etc.

* Thus we calculate a specific form of loudness loss, which strictly speaking does not necessarily comply with the CCITT/NOSFER definition. In view of the additivity problems indicated in Section 1.4 and in the beginning of Section 3.1 we shall nevertheless consider this loudness loss to represent the RE.

The inevitable result is that even general formulas based partly on theoretical considerations, and partly on empirical data, contain so many parameters that without the help of values measured direct, it is hardly possible to obtain more insight into the matter. Therefore, for our purpose, i.e. the investigation of feeding loss, we shall compose a simple model of the carbon microphone, direct based on the results of measurements. Measuring the characteristics of carbon microphones is and always has been a difficult and somewhat doubtful task, because of the fundamental drawback of this type of microphone, namely that it is instable even on shorter term. Moreover, the characteristics of the microphone depend on the conditions during the preceding period. This lastmentioned effect makes it necessary to condition the microphone, usually by moving it in a specific way, just before each measurement. However, conditioning means that the granules in the carbon chamber are put in a new position so that variations can be expected in the results. This drawback can to some extent be eliminated by performing a sufficient number of measurements under the same conditions, and by taking the average of all the values measured. In practice the number of measurements can often be rather limited only, and we should therefore be aware of the effect of certain variations in the (average) results.

For our purpose, i.e. to obtain an insight into the behaviour of the carbon microphones used in the Netherlands telephone sets, measurements were made on nine microphones, three from each of the three makes frequently used in the network. All these microphones have been derived from the same basic design. The nine microphones were between one and four years old.

The values of measured quantities, which will be used in this section, each relate to the mean value of the results of 45 measurements for each condition; five successive measurements of each of the nine microphones.

A simplified electrical representation of the carbon microphone is given in Figure 3.2a. In this diagram it is assumed that there is a d.c. current I_m, and that the microphone resistance R_m shows a variation ΔR_m caused by speech. Z_u represents the load impedance for a.c. Figure 3.2b gives the diagram for a.c. conditions.

It is a well-known fact that the d.c. resistance (i.e. the quotient of d.c. voltage and d.c.

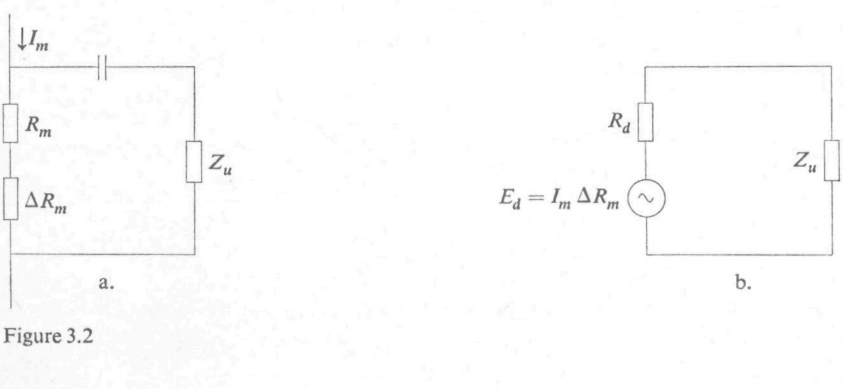


Figure 3.2

current) of a carbon microphone changes with the magnitude of the feeding current [4, 15], because of the non-linear relationship between voltage and current. From this it follows that there is a difference between the d.c. resistance and the differential resistance, the latter being relevant to small a.c. signals.* Thus in the a.c. diagram the microphone resistance is represented by the a.c. resistance R_d.** The values of both resistances, R_m and R_d, were measured in five feeding conditions, corresponding to a 48 V, 800 Ω feeding system and loop resistances of 0, 250, 500, 750 and 1000 Ω. During the measurements speech conditions were simulated by a sound source producing noise with a spectrum limited to the telephone band. The results are given in Table 3.2.

Table 3.2

R_l	R_m	R_d	R_m/R_d
0 Ω	187 Ω	116 Ω	1.61
250	211	136	1.55
500	245	152	1.61
750	261	166	1.57
1000	276	175	1.58

The most remarkable result in this table is the almost constant ratio between R_m and R_d with a value of 1.6, which ratio is also very clear in Figure 3.3 where the measured values of R_m and R_d have been plotted and, for the sake of clearness, interconnected by straight lines.

This ratio between R_m and R_d is the most accurate information contained in Table 3.2, because after each conditioning, values of R_m and R_d were measured simultaneously. Moreover, the value of the ratio does not vary much amongst different microphones, nor amongst successive measurements on each microphone. Relations between values of R_m (or R_d) in different feeding conditions, however, are much more liable to variations, because they were measured after the microphone had been conditioned again. So, the first conclusion to be drawn from Table 3.2 is that for the carbon microphone used in the Netherlands telephone network the following relation appears to apply:

$$R_m = 1.6\, R_d \text{ or } \frac{V_m}{I_m} = 1.6 \frac{\mathrm{d}V_m}{\mathrm{d}I_m} \qquad (3\text{–}2)$$

where V_m is the d.c. voltage over the microphone.

* Means [15] indicates a (rather small) difference between the slope of the d.c. V-I characteristic and the a.c. resistance, due to thermal expansion of the diaphragm electrode in the carbon chamber. In our simple model we shall neglect this detail; the results we obtain being in good agreement with values of feeding loss measured direct (see Section 3.4).

** When calculating the a.c. output voltage, the variations of R_d caused by speech can be neglected because these resistance variations and also the signal currents are usually relatively small.

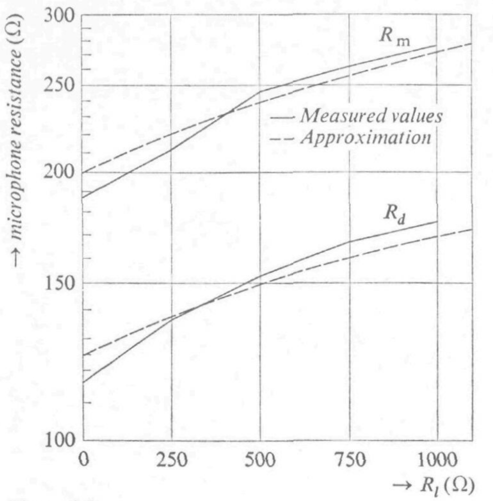


Figure 3.3

This relation suggests a relationship between I_m and V_m which can in general be described as: $V_m = p\, I_m{}^q$; so:

$$R_m = \frac{V_m}{I_m} = p\ I_m{}^{q-1} \text{ and } R_d = \frac{\mathrm{d}V_m}{\mathrm{d}I_m} = p\ q\ I_m{}^{q-1}$$

From (3–2) it follows that $q = \dfrac{1}{1.6} = 0.625$.

The value of the constant p should be such that the best approximation of the values of R_m and R_d as given in Table 3.2 is obtained. A 'least square' approximation results in $p = 55$.

So:

$$V_m = 55\, I_m{}^{0.625}\ and\colon R_m = 55\, I_m{}^{-0.375},\ R_d = \frac{55}{1.6} I_m{}^{-0.375} \tag{3–3}$$

The values of R_m and R_d corresponding to different feeding conditions can be calculated (see also Section 3.4 and Table 3.4); the results are given in Figure 3.3 (dotted curves). Taking into account the possible variations inherent in carbon microphones, we can conclude that there is a fair agreement.

The resistance values discussed so far, relate to conditions that speech simulating noise is applied to the microphone. In practice, however, the resistance of the microphone is also of interest in conditions when the microphone is not activated by sound. It is a well-known fact, that sound will increase the resistance of a carbon microphone, because of the agitation of the carbon granules. This effect was also measured with our microphones. Without noise the values of resistances were about 12.5% lower than in Table 3.2. These lower values should be taken into account when considering the impedance of the telephone set in receiving conditions.

Next we should investigate the instantaneous variations in resistance due to sound applied to the diaphragm of the microphone. Owing to these variations this device can be used as an electro-acoustical transducer, its action being modulation of direct current. In this respect the relative variation in resistance is an important quantity. If I_m is the (mean) value of the direct current through the microphone the following equation applies: $\frac{\Delta R_m}{R_m} = \frac{I_m \Delta R_m}{I_m R_m}$ and this is proportional to $\frac{E_d}{V_m}$, where E_d represents the e.m.f. of the a.c. signal (see Figure 3.2).

The series of measurements which provided the data for our study of resistance, also included d.c. voltage over the microphone (V_m) and the a.c. voltage (E_d) due to noise sound applied to the microphone. During the measurements the value of Z_u was high compared with the microphone impedance.

For our purpose, i.e. determination of feeding loss, we are not interested in absolute signal voltages (which will depend on the sensitivity of the microphone and on sound pressure), but in variations with feeding conditions. Therefore in Table 3.3 the measuring results are presented as relative values, normalized to the value for the condition $R_l = 0\ \Omega$.

Table 3.3

R_l	Normalized values of		
	V_m	E_d	E_d/V_m
0 Ω	1	1	1
250	0.854	0.886	1.037
500	0.775	0.815	1.051
750	0.688	0.765	1.111
1000	0.620	0.693	1.117

In this table we see that according as the d.c. voltage decreases, the relative resistance variation (which is proportional to E_d/V_m) increases. The results of Table 3.3 are also plotted in Figure 3.4. We can conclude that the relation between E_d and V_m in this diagram can be very well approximated by a straight line. Because of the logarithmic scales this means that E_d is proportional to V_m^s, where s is a constant indicating the slope of the line. By means of the 'least square method' the value of s was determined which results into the best fit to the values of Table 3.3. We found: $s = 0.75$.

So: E_d is proportional to $V_m^{0.75}$ (3-4)

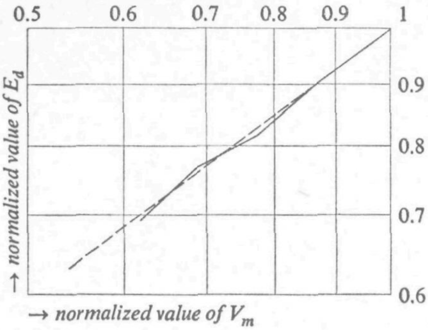


Figure 3.4

This relation enables us to calculate the variation in a.c. voltage under different feeding conditions.
Other measurements showed that the sensitivity/frequency characteristic of the microphones does not change significantly with different feeding conditions.

3.4 *Values of feeding loss*

As far as direct current is concerned the complete feeding circuit can be represented by Figure 3.5, which is a simplification of Figure 3.1. For the standard telephone set in the Dutch network a value of 50 Ω can be quoted for R', the resistance of the line winding of the hybrid coil. The resistance of the balancing network, R_c, is 400 Ω. With the help of formula (3–3) we can calculate the corresponding values of I_m, V_m and R_m for each feeding condition.

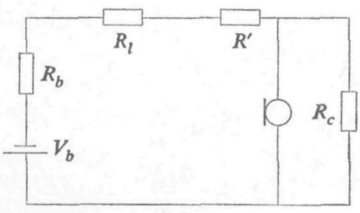


Figure 3.5

First we shall consider the standard feeding system with $V_b = 48$ V, $R_b = 800$ Ω. The equations could not be solved by analytical means and it was necessary to employ an iterative process. Therefore, the exact relationships between loop resistance on the one hand and I_m, V_m or R_m on the other hand, cannot be represented by simple formulas. The calculated results are given in the first columns of Table 3.4. For practical calcula-

Table 3.4

Feeding system 48 V, 800 Ω

R_l	I_m	V_m	R_m	R_d	a_f
0 Ω	32.65 mA	6.479 V	198.5 Ω	124.0 Ω	0.00 dB
100	29.10	6.030	207.2	129.5	0.59
200	26.21	5.649	215.5	134.7	1.14
250	24.96	5.478	219.5	137.2	1.39
300	23.81	5.320	223.4	139.6	1.64
400	21.79	5.033	230.9	144.3	2.11
500	20.06	4.780	238.2	148.9	2.54
600	18.58	4.555	245.2	153.2	2.95
700	17.28	4.353	251.9	157.5	3.34
750	16.69	4.260	255.2	159.5	3.52
800	16.14	4.171	258.5	161.6	3.70
900	15.13	4.006	264.8	165.5	4.05
1000	14.22	3.855	271.0	169.4	4.38

tions it is useful to approximate the relationship between microphone resistance and loop resistance, so that it can be described by a simple formula. With a good degree of accuracy (deviations smaller than 1 %) this was possible for the values of loop resistance occurring in practice. The relationship was:

$$R_m = 200 + 0.0728\, R_l\, \Omega \qquad (3\text{-}5)$$

and consequently

$$R_d = 125 + 0.0455\, R_l\, \Omega \qquad (3\text{-}6)$$

The values of V_m at $R_l = 0\ \Omega$ and at other values of R_l can be inserted in formula (3–4) in order to find the variation in the e.m.f. of the generated a.c. signal, caused by the insertion of the loop resistance. In the calculation of the a.c. output signal of the telephone set, the transmission circuit in the right-hand part of Figure 3.1 should be taken into account. It is clear that generally the impedance of the telephone receiver will influence the transmission conditions between microphone and line terminals of the telephone set. But there is one condition in which this influence disappears, namely in the case that both branches of the hybrid circuit are balanced. Because of the turns ratio 1 : 0.6 and the balance impedance of 400 Ω (see Figure 3.1) the corresponding line impedance is about 600 Ω. In that case the transmission from microphone to line can be derived from the reduced diagram in Figure 3.6.
A similar effect occurs in the receiving direction. Here generally the transmission conditions between line and telephone receiver will be influenced by the microphone resistance in a rather complicated way. But in the balanced condition (i.e. with a line

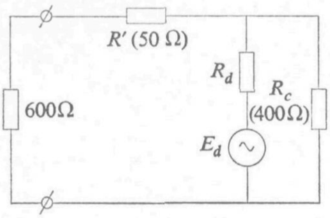


Figure 3.6

impedance of 600 Ω), microphone and receiver are completely decoupled. In the first instance we shall use this condition when determining the feeding loss, in order to exclude the frequency dependent influence of the telephone receiver. Later on, after having considered the impedance of the telephone set and the insertion loss of the subscriber's line, we shall deduce (in Section 3.8) the additional correction necessary if real terminating conditions are taken into account.

With the help of the diagram in Figure 3.6 we can calculate the relative changes in a.c. output voltage compared with zero line length conditions. These relative changes expressed in dB give the value of the feeding loss. The results are given in the last column of Table 3.4 indicated by α_f.

The results calculated are worth a closer consideration. In Figure 3.7 the values of feeding loss are plotted versus loop resistance. Our first conclusion is that an approximation by linear relationship is not very suitable. The rule of thumb sometimes used in the Netherlands giving a feeding loss of 0.44 dB per 100 Ω loop resistance belongs under this category.

The values calculated for feeding loss in Table 3.4 can be compared with those resulting from measurements. First of all we can obtain values direct from the data used in Section 3.3. For that purpose we used the measured values of E_d and R_d for calculating the values of feeding loss for each individual microphone. The mean values of the results are given in Table 3.5.

Table 3.5

R_l	α_f
250 Ω	1.47 dB
500	2.62
750	3.44
1000	4.49

The values of Table 3.5 are indicated in Figure 3.7, and we can conclude that there is a good agreement; the maximum deviation is about 0.1 dB. Apparently the approximations used in the calculations are reasonably accurate.

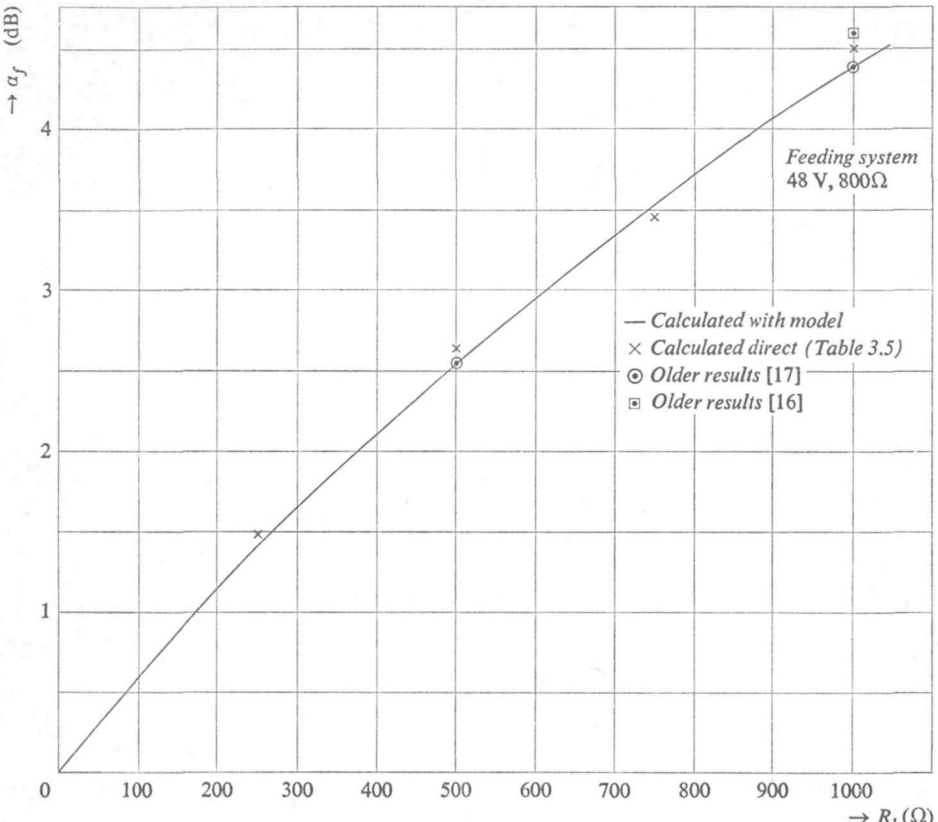


Figure 3.7

Over the years other, more or less extensive, measurements have been carried out in order to determine the values of feeding loss objectively. Results derived from internal PTT reports [16, 17] are also indicated in Figure 3.7. In one case the available values needed a small correction, because in these measurements a slightly different load impedance was used. When calculating this correction we used the values of R_d given in Table 3.4, because such values were not available about the microphones involved. The error which might creep in in this way, is neglegible; the correction itself being even smaller than 0.1 dB. Once more there is a good agreement with the results given in Table 3.4. The conclusion seems justified that the model we have used for the calculation of feeding loss is reliable.

The relationship between feeding loss and loop resistance can be described with good accuracy (maximum deviation about 0.03 dB within the range of interest) by the formula:

$$\alpha_f = 5.86\ 10^{-3}\ R_l - 1.51\ 10^{-6}\ R_l^2\ \text{dB} \qquad (3\text{-}7)$$

This formula is valid for the 48 V, 800 Ω system.
We can compose a table similar to Table 3.4 for the 60 V, 1000 Ω feeding system. In order to obtain a correct survey of the sensitivity of microphones in the network, we shall again use the zero line condition in the 48 V system as reference. This means that for the 60 V system the feeding loss for zero line length will not equal zero. The results are given in Table 3.6.

Table 3.6

Feeding system 60 V, 1000 Ω

R_l	I'_m	V'_m	R'_m	R'_d	α'_f	R_{eq}
0 Ω	34.14 mA	6.663 V	195.2 Ω	122.0 Ω	–0.23 dB	–36.2 Ω
100	31.03	6.276	202.3	126.4	0.26	43.1
200	28.40	5.939	209.1	130.7	0.72	122.5
300	26.16	5.641	215.6	134.8	1.15	202.0
400	24.23	5.377	221.9	138.7	1.55	281.5
500	22.54	5.140	228.0	142.5	1.93	361.0
600	21.06	4.926	233.9	146.2	2.29	440.5
700	19.75	4.732	239.6	149.8	2.63	520.0
800	18.58	4.555	245.2	153.2	2.95	599.6
900	17.53	4.393	250.6	156.6	3.26	679.2
1000	16.59	4.243	255.8	159.9	3.55	758.8

These results can also be represented by simple formulas, which provide a good approximation:

$$R'_m = 196.5 + 0.0606\, R_l\, \Omega \qquad (3\text{–}8)$$

$$R'_d = 122.8 + 0.0379\, R_l\, \Omega \qquad (3\text{–}9)$$

$$\alpha'_f = -0.22 + 4.85\; 10^{-3}\, R_l - 1.09\; 10^{-6}\, R_l^2 \text{ dB} \qquad (3\text{–}10)$$

To enable easy comparison with results of the standard feeding system 48 V, 800 Ω, we introduce a new quantity, the equivalent loop resistance R_{eq}, i.e. the loop resistance in the 48 V, 800 Ω system causing the same value of feeding loss as the situation under consideration. This means that the d.c. current (I_m), the voltage (V_m) and the resistances of the carbon microphone are also the same. The resulting values of R_{eq} are listed in the last column of Table 3.6.
These values of R_{eq} can very precisely be described by the formula:

$$R_{eq} = -36.3 + 0.795\, R_l\, \Omega \qquad (3\text{–}11)$$

3.5 *Influence of variations in feeding systems*

The calculations in the preceding section showed the influence of the feeding conditions on the sending sensitivity of the telephone set. In practice, the battery voltage (V_b) and the resistance of the feeding bridge (R_b) can show considerable deviations from their nominal values. These deviations will also influence the sending sensitivity. A similar effect is brought about by the insertion of additional resistance in the subscriber's loop, as is the case with subscribers equipped with an additional technical facility for automatic change-over between two sets.* This additional resistance can be considered as an extra variation of R_b.

In our investigation on the effect of variations of feeding systems we shall indicate the relative deviation from the nominal value of battery voltage V_b by v; the deviation from the nominal resistance R_b will be indicated by r. We again introduce an equivalent loop resistance R_{eq} i.e. the loop resistance in the nominal feeding system causing the same sending sensitivity as is the case under the condition in question. This leads to the equation (see Figure 3.6):

$$\frac{V_b(1+v)}{R_b + R_l + r + R' + \dfrac{400\,R_m}{400 + R_m}} = \frac{V_b}{R_b + R_{eq} + R' + \dfrac{400\,R_m}{400 + R_m}} \qquad (3\text{–}12)$$

For the 48 V system R_m can be replaced by formula (3–5). Thus we can substitute:

$$\frac{400\,R_m}{400 + R_m} = 400\,\frac{200 + 0.0728\,R_{eq}}{600 + 0.0728\,R_{eq}} \approx 133\,(1 + \frac{0.0728}{300}\,R_{eq})$$

Now equation (3–12) can be solved and for the 48 V, 800 Ω feeding system we find:

$$R_{eq} = \frac{R_l - 983v + r}{1 + 1.03v}\,\Omega \qquad (3\text{–}13)$$

We see that variations in the feeding system can be converted into variations of loop resistance. Thus, the corresponding variations in the sending sensitivity can, in a certain sense, be represented as variations in feeding loss. The change in sending sensitivity corresponding to R_{eq}, as compared with the sensitivity with $R_l = 0$ in a nominal feeding system, can be calculated by substitution of R_{eq} instead of R_l in formula (3–7). Assuming that the deviations r and v are relatively small, we can neglect factors with v^2, r^2 and rv. Then we find:

$$\alpha_f = 5.86\;10^{-3}\{R_l(1-1.03v) - 983v + r\} - 1.51\;10^{-6}\{R_l^2(1-2.06v) + 2R_l(r-983v)\}\text{dB}$$

* The additional resistance of the relays used for this purpose is by-passed by a capacitor so that the transmission of speech signals is not affected.

The deviation from the nominal value is

$$\Delta \alpha_f = (5.86\ 10^{-3} - 3.02\ 10^{-6} R_l)\{r - v(983 + 1.03\ R_l)\}\ \text{dB} \tag{3-14}$$

An analogous calculation can be made for the 60 V, 1000 Ω system, using formulas (3-8) and (3-10). We find:

$$\alpha'_f = -0.22 + 4.85\ 10^{-3}\{R_l(1-1.03v) - 1182v + r\}$$
$$-1.09\ 10^{-6}\{R_l^2(1-2.06v) + 2R_l(r-1182v)\}\ \text{dB}$$

$$\Delta \alpha'_f = (4.85\ 10^{-3} - 2.18\ 10^{-6} R_l)\{r - v(1182 + 1.03\ R_l)\}\ \text{dB} \tag{3-15}$$

With the help of these formulas the influence of variations in the feeding systems can be calculated.

3.6 *The impedance of the telephone set*

For the calculation of the insertion loss of the subscribers' lines we need to know the impedance of the telephone set. From the circuit diagram of the transmission circuit inside the telephone set (see right-hand part of Figure 3.1) we can deduce that the impedance of the telephone set will be dependent on the impedances of the microphone and the telephone receiver. This receiver is in the standard set of the magnetic type, and its impedance is considerably inductive. In the speech frequency band the impedance of the microphone can be considered purely resistive, with different values for d.c. and (small) a.c. signals. These values depend on feeding conditions and on sound pressure applied to the microphone (see Section 3.3).

The impedance of the telephone set was measured with several values of microphone resistance. The results showed that both real and imaginary part of the impedance of the telephone set changed to about the same extent. These changes are substantially proportional to changes in microphone resistance; at least for such values of this resistance corresponding to practical feeding conditions. The relative variation in impedance of the set is approximately one third of the relative variation in microphone resistance. This remarkable result has been verified by calculations on the transmission circuit in the telephone set. It turned out that this ratio of 1/3 to a large extent is independent of the impedance of the receiver. The value of the ratio is determined, at least for the impedances applicable in our study, by the turns ratio of the hybrid coil and the impedance of the balancing network.

So the impedance of the telephone set under a feeding condition X can be approximated by:

$$Z_{tx} = Z_{to}\left(1 + \frac{R_{dx} - R_{do}}{3\,R_{do}}\right) \tag{3-16}$$

where Z_{tx} and R_{dx} indicate the impedance of the telephone set and the resistance of

the microphone respectively under feeding condition X. Z_{to} and R_{do} correspond to a reference condition.
The choice of the value Z_{to} is somewhat arbitrary, because of tolerances in the impedances of receivers, hybrid coils and balancing network. We derived values from information available within PTT [18] using interpolation for obtaining data at the frequencies used in our calculations (see Table 3.1). For the reference condition we use the zero line length condition in a 48 V, 800 Ω feeding system. The corresponding nominal values of Z_{to} are given in Table 3.7.

Table 3.7

Freq.	Z_{to}
473 Hz	305 + j 220 Ω
663	350 + j 280
928	430 + j 340
1299	505 + j 360
1818	625 + j 450
2545	825 + j 500

The impedance values under other feeding conditions (also in another feeding system) can be found by inserting in formula (3–16) the appropriate value of R_{dx}, calculated with the help of formulas (3–3).

3.7 *Values of RE of subscribers' lines*

For the calculation of the RE we need to know the insertion loss at six frequencies (see Section 3.2). Insertion loss can only be determined if the cable parameters and the terminating impedances at both ends are known. The general form of the impedance at the subscriber's end is described by formula (3–16). In our calculations we shall first use values corresponding to a 48 V feeding system. Then, taking into account the relation given in formula (3–6), formula (3–16) becomes:

$$Z_{tl} = Z_{to}(1 + 1.21\ 10^{-4}R_l) \tag{3–17}$$

The values of Z_{to} are given in Table 3.7.
For the terminating impedance at the local exchange end of the subscriber's line we use 800 Ω, the nominal impedance in this part of the telephone network (see also Section 5.1).
The electrical characteristics of the subscribers' lines in the model network are given in Section 2.9. In the case a subscriber's line contains two or more parts of different

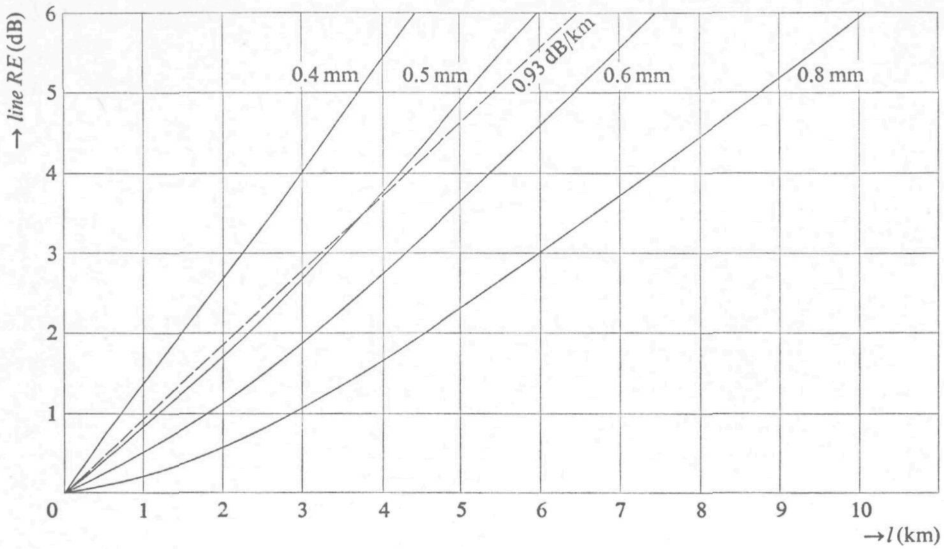


Figure 3.8

types of cable in cascade, as was apparently the case with a number of lines in the survey (see Section 2.5), the exact calculation of the insertion loss is rather complicated. However, for the cable types used most frequently, the return loss at the joint between different cables is reasonably high (see Section 5.1) and only a small proportion of the signal is reflected. Consequently, the transmission loss is affected only slightly. In our calculations with regard to the lines in the survey, we can consider the characteristics to be equally distributed over the complete length.

With the above data we can calculate the RE by means of the method discussed in Section 3.2. The results concerning several types of cable are plotted in Figure 3.8. Apparently the relationship between RE and line length can differ considerably from linear. This was to be expected because it is a well-known fact that insertion loss shows a similar picture. Thus planning rules based on a linear relationship provide only a coarse approximation. In Figure 3.8 a dotted line indicates values corresponding to the rule of thumb used in the Netherlands (formula (3–1)). In spite of the rather unreliable way in which it was established, it provides about the best linear approximation for lengths of up to 5 km. A better approximation for 0.5 mm cable can be obtained by a somewhat extended formula:

$$RE_{0.5} = 0.769l + 0.0421l^2 \text{ dB} \quad (l \text{ in km}) \tag{3–18}$$

Now the maximum deviation from the calculated values of line RE is about 0.01 dB for lengths of up to 5 km, which is amply sufficient for our purpose.

It is worth noting that the variations in microphone resistance owing to variations in feeding current (Table 3.4), have a small influence on insertion loss and consequently on line RE. Values of line RE calculated with a constant microphone resistance of 124 Ω (the value at zero line length) for 0.5 mm cable show the following increases in respect to those with a varying microphone resistance: 1 km: 0.01 dB, 3 km: 0.04 dB, 5 km: 0.06 dB. Comparison of the values of microphone resistance in Tables 3.4 and 3.6 shows that the difference in line RE between the 48 V and the 60 V feeding system will even be much smaller. The actual difference for 5 km cable amounts to only 0.01 dB. We can conclude that the effect of the difference in feeding system on line RE is negligible. Of course this will also apply to the effect of variations in the feeding systems. The effect of the lower values of the microphone resistance in receiving conditions (see Section 3.3) was also investigated. Calculations on 0.5 mm cable showed the following differences in RE with respect to conditions with speech: 1 km: +0.02 dB; 3 km: +0.03 dB; 5 km: +0.03 dB. Again the differences are so small that they can be neglected. So we can conclude that the values of the line RE of a subscriber's line for sending and receiving are equal and independent of the feeding system.

3.8 *Values of RE for sending and receiving direction*

The values of RE calculated in Section 3.7 only take into account the loss introduced by insertion of a certain length of cable between 800 Ω and an impedance of the telephone set corresponding to that line length. But what we need is the total effect of insertion of the cable, namely the difference between conditions with a certain line length inserted and those for zero line length. In the latter situation the set has another impedance than the one used in the calculation of insertion loss.
Moreover, there is the additional effect of feeding loss in the sending direction. To avoid the frequency dependent influence of the telephone receiver, the feeding loss was calculated in Section 3.4 with a line impedance of 600 Ω; but this is not in accordance with reality.
These considerations show that additional corrections are necessary. For this purpose we use Figure 3.9 which gives a simplified representation of the situations concerned. In Figure 3.9a the conditions for zero line length are indicated; in Figure 3.9c those

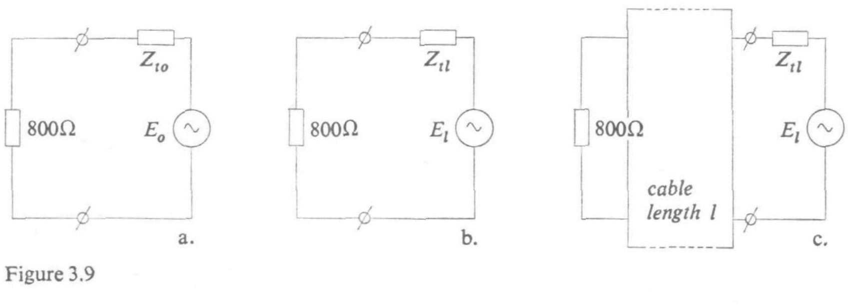


Figure 3.9

with an inserted line length l. The generator with e.m.f. E_l and impedance Z_{tl} represents the sending telephone set under the feeding condition corresponding to the line length l. The total effect of the insertion of a line length l is the difference between a and c in Figure 3.9. The process can be divided into two steps by the introduction of an imaginary intermediate situation b which represents the set under the feeding condition corresponding to line length l, but terminated in 800 Ω. The difference between situation b and c corresponds exactly to the insertion loss as calculated. The difference between a and b determines the feeding loss, in a similar way as assumed in the calculations of Section 3.4, however with a load impedance of 800 Ω. A simple calculation shows that the values of feeding loss as calculated for a load impedance of 600 Ω should be corrected by

$$\alpha_c = 20 \log_{10} \left| \frac{800 + Z_{tl}}{800 + Z_{to}} \; \frac{600 + Z_{to}}{600 + Z_{tl}} \right| \text{dB} \tag{3-19}$$

For receiving conditions the insertion of a line length l can be divided into two steps in a similar way (see Figure 3.10).

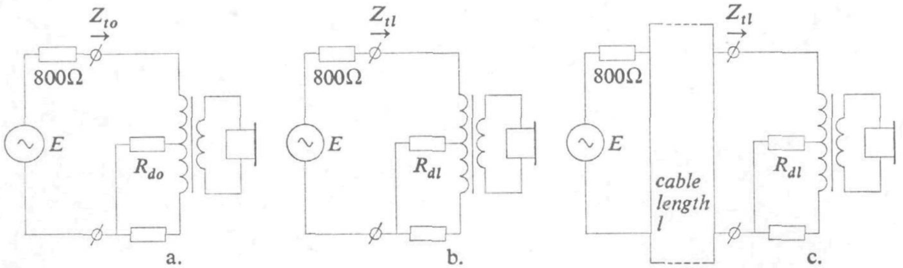


Figure 3.10

Now the intermediate situation b represents the set under conditions corresponding to a line length l (but without that line). The impedance of the set and the transmission conditions inside the set have changed, compared with condition a, because of the variation in microphone resistance. The difference between b and c once more provides the insertion loss of the line. If in the situations a and b the impedance of the generator would be 600 Ω instead of 800 Ω, then the two branches of the hybrid circuit inside the telephone set would be balanced (see Section 3.4), and the signal received at the receiver would not be influenced by the microphone resistance. Proceeding on this, it will be easy to calculate the difference in received signal between situation a and b. The resulting correction to be added to the calculated values of insertion loss is also expressed by formula (3–19). In this formula the results of formula (3–17) can be substituted. We find

$$\alpha_c = -20 \log_{10} \left| \left(\frac{1}{1 + \dfrac{1.21\ 10^{-4} R_l Z_{to}}{800 + Z_{to}}} \right) \left(1 + \frac{1.21\ 10^{-4} R_l Z_{to}}{600 + Z_{to}} \right) \right| \text{dB}$$

With practical values of Z_{to} and R_l we can use the approximation:

$$\alpha_c \approx -20 \log_{10} \left| 1 + 1.21\ 10^{-4} R_l \frac{200\, Z_{to}}{(800 + Z_{to})\,(600 + Z_{to})} \right| \text{dB} \quad \text{or}$$

$$\alpha_c \approx -20 \log_{10} \left\{ 1 + 242\ 10^{-4} R_l \left| \frac{Z_{to}}{(800 + Z_{to})\,(600 + Z_{to})} \right| \cos\varphi \right\} \text{dB}$$

where φ represents the phase angle of the last (complex) fraction. Further approximation results in:

$$\alpha_c \approx -210\ 10^{-3} R_l \left| \frac{Z_{to}}{(800 + Z_{to})\,(600 + Z_{to})} \right| \cos\varphi \text{ dB} \tag{3-20}$$

It can be shown that this form is substantially independent of values of Z_{to} in a large range around 600 and 800 Ω.* The values of Z_{to} we use in our calculations (Table 3.7) are such that α_c will be nearly frequency-independent, which means that the RE of the correction factor can be calculated separately and that its value can be added afterwards. For the values of RE corresponding to α_c we find:

$$RE_c = -8\ 10^{-5}\, R_l \text{ dB} \tag{3-21}$$

We conclude that for practical values of R_l the correction is small, namely smaller than 0.1 dB.

For the 60 V feeding system we can make similar calculations using appropriate values for Z_{tl}. The differences with values obtained by means of formula (3-21) are so small (less than 0.02 dB) that they can be neglected. Of course the same conclusion will even be more valid for the effect of variations in each of the feeding systems.

The effect of the lower impedance in receiving conditions can also be calculated; as could be expected, the influence on RE_c is negligible (for practical values of R_l smaller than 0.01 dB). So the conclusion is that formula (3-21) can be used in all cases.

The total RE for sending (RE_s) is given by the sum of the line RE as calculated in Section 3.7, the feeding loss as described in Section 3.4 and the correction given by formula (3-21). Of course, in the total RE for receiving (RE_r) the feeding loss should be omitted.

With 0.5 mm conductors and a 48 V feeding system we have to add the values given by formulas (3-18), (3-7) and (3-21). The result is (with l is cable length in km):

$$RE_s = 1.775l - 0.0036l^2 \text{ dB} \tag{3-22}$$

* The last part of formula (3-20) shows a resemblance to the form occurring when the output power of a generator with finite internal resistance is calculated. It is well-known that this power is nearly constant with values of the load impedance in a wide range around the value of the internal resistance.

For the receiving direction we find:

$$RE_r = 0.755l + 0.0421l^2 \text{ dB} \tag{3-23}$$

With 0.5 mm cable in a 60 V feeding system the values are:

Sending: $RE'_s = -0.22 + 1.599l + 0.0091l^2$ dB (3-24)

Receiving: see formula (3-23).

3.9 *Distributions of RE for sending and receiving direction**

For the model network described in Section 2.9 the distribution of the RE's can easily be calculated by means of formulas (2-9), (3-22), (3-23) and (3-24). For the value of the mean and the standard deviation of the RE's, taking into account nominal values for the feeding systems, we find:

Sending direction:	48 V feeding system:	$\mu_{RE_s} = 3.21$ dB	$\sigma_{RE_s} = 2.26$ dB
	60 V feeding system:	$\mu'_{RE_s} = 2.73$ dB	$\sigma'_{RE_s} = 2.12$ dB
Receiving direction:		$\mu_{RE_r} = 1.58$ dB	$\sigma_{RE_r} = 1.27$ dB

Similar calculations could be made for the subscribers' lines contained in the survey (see Chapter 2). For each line the values of feeding loss, line RE and correction factor were calculated from the data available on length and loop resistance. For the resulting distribution we found:

Sending direction:	48 V feeding system:	$m_{RE_s} = 2.99$ dB	$s_{RE_s} = 2.17$ dB
	60 V feeding system:	$m'_{RE_s} = 2.53$ dB	$s'_{RE_s} = 2.03$ dB
Receiving direction:		$m_{RE_r} = 1.46$ dB	$s_{RE_r} = 1.19$ dB

The cumulative distributions of these nominal values calculated for RE_s and RE_r have been plotted in Figure 3.11 and Figure 3.12. There is only little difference between the results for the model network and those for the lines contained in the survey. This difference can easily be explained by the difference in loop resistance which influences both feeding loss and line RE. In practice the results of the model network are of increasing importance (see Section 2.8).

Although the values of the mean and the standard deviation calculated above give useful information on the distributions in question, it would be a good thing to obtain more details concerning the extreme values at both ends of the distributions, because

* These values relate to subscribers' lines which direct connect telephone sets to the local exchange. For extension stations usually feeding current is supplied from the PBX (see Section 1.3) and the subscriber's line does not contribute to the feeding loss. On the other hand, for calls from and to extensions via the public network some additional losses will be introduced by the PBX and the extension line. Statistical information on these aspects was not available.

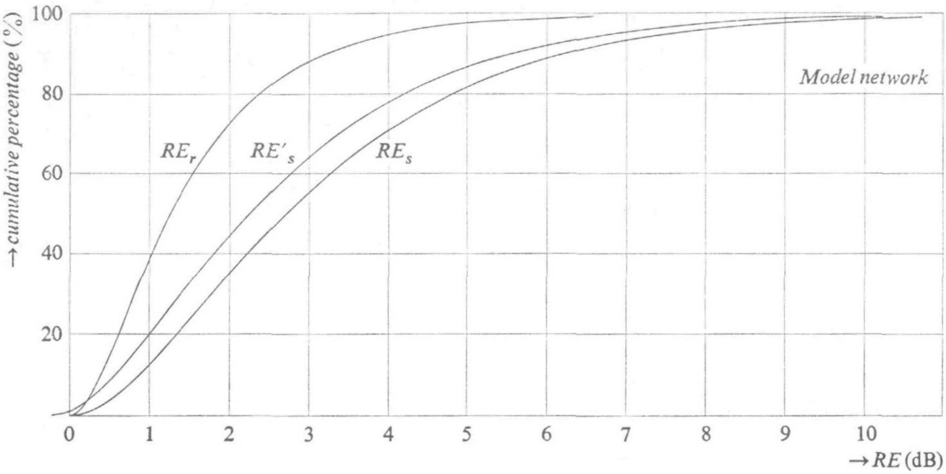


Figure 3.11

too loud and too weak calls are important in view to subscriber's appreciation (see Section 4.1). For this purpose the 5% and 95% points, and the 1% and 99% points of the distributions have been determined; the ranges between these points contain 90% and 98% of the population respectively. The results are given in part A of Table 3.8. The last columns show that the ranges between the limits indicated above, as related to the standard deviation of the distribution concerned, are almost constant (values between brackets).

Table 3.8

Values of RE in dB		μ	σ	1%	5%	95%	99%	5%–95%	1%–99%
A Nominal values	RE_r	1.58	1.27	0.10	0.25	4.04	6.09	3.79(3.0σ)	5.99(4.7σ)
	RE_s	3.21	2.26	0.24	0.57	7.59	10.68	7.02(3.1σ)	10.44(4.6σ)
	RE_s'	2.73	2.12	0.00	0.30	6.85	9.76	6.55(3.1σ)	9.76(4.6σ)
B Including variations feeding syst.	RE_{sv}	3.21	2.30	–0.10	0.45	7.60	10.70	7.15(3.1σ)	10.80(4.7σ)
	RE_{sv}'	2.73	2.16	–0.36	0.15	6.87	9.81	6.72(3.1σ)	10.17(4.7σ)
C National situation	RE_{rn}	1.58	1.27	0.10	0.25	4.04	6.09	3.79(3.0σ)	5.99(4.7σ)
	RE_{sn}	2.97	2.24	–0.30	0.29	7.27	10.29	6.98(3.1σ)	10.59(4.7σ)

The results in part A of Table 3.8 relate to nominal values of the RE, i.e. with nominal terminating conditions and nominal values of the feeding system.
As to the terminating conditions, both the impedance at the exchange end and that of the telephone set will in practice show deviations from their nominal values. However, such deviations have only a minor influence on insertion loss and by that on the line

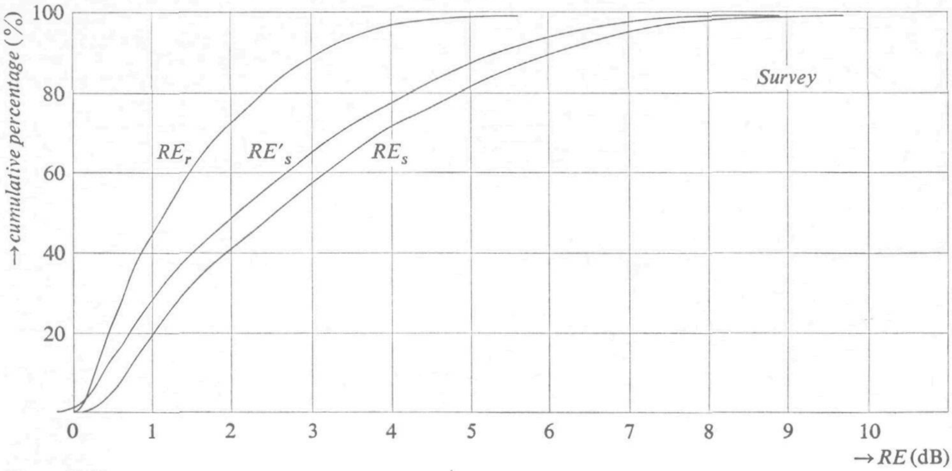


Figure 3.12

RE. As compared with variations of line RE resulting from variations in line length, the deviations in line RE are so small that they can be neglected. For example: a variation of 20% in the values of the impedance of the telephone set results in a variation of only about 0.1 dB or smaller in the line RE (see also Table 5.13).

The values of feeding loss, apart from the effect of variations in the feeding system, will be influenced by the individual properties of microphones, which can deviate from the average properties we used in our calculations. However, it turns out that feeding loss is only slightly influenced by the absolute values of microphone resistance. A change of 25% in the values of R_m and R_d in formula (3–3) will result in a change of only about 5.5% in the values of feeding loss. Much more important are the variations in sensitivity of carbon microphones resulting from manufacturing tolerances, and from the instability inherent in this type of microphone. As these variations are not directly related to the subscriber's line we shall not go into the subject, but keep it in mind in our following considerations.

Concerning the effect of variations in the feeding systems, given by formulas (3–14) and (3–15), we assume that the distribution of the variations v and r (see Section 3.5) have a mean value 0 and a standard deviation of s_v and s_r respectively; these variations are independent of each other. Now the distribution of the resulting variations in sending sensitivity can be calculated. The variations in sensitivity are dependent on R_l and consequently on RE_s, which might complicate the calculations. However, for each value of R_l the mean value of the variations in sensitivity will be 0, because of the assumptions made with regard to v and r. Hence the covariance of the two variables RE_s and variation in the sending sensitivity resulting from variations in the feeding system, will also be 0. Thus the standard deviations of both variables can be calculated separately and added in the usual way.

With a 48 V feeding system and the model network the result is:

$$\mu_{\Delta\alpha_f} = 0, \quad \sigma^2_{\Delta\alpha_f} = 39.5\, s_v^2 + 2.45\, 10^{-5}\, s_r^2 \tag{3–25}$$

With a 60 V feeding system we find:

$$\mu_{\Delta\alpha'_f} = 0 \quad \sigma^2_{\Delta\alpha'_f} = 38.0\, s_v'^2 + 1.75\, 10^{-5}\, s_r'^2 \tag{3–26}$$

In order to obtain an idea about the magnitude of the variations involved, we shall make a rough estimate of the variations in feeding systems, based on tolerances used in practical specifications and in system calculations.* The battery voltage V_b is influenced by charging and loading conditions, internal resistance, temperature, etc. A standard deviation of 3.5% seems a reasonable estimate for the variations, so that $s_v = 0.035$ and $s'_v = 0.035$. Variations in the resistance R_b of feeding bridges are due to production tolerances, ageing, influence of temperature, etc. Including the effect of possible additional resistance at subscribers' premises (see Section 3.5), we can estimate that $s_r = 70\ \Omega$ in the 48 V system and that $s'_r = 85\ \Omega$ in the 60 V system. These values can be inserted in formulas (3–25) and (3–26). The results are:

$$\text{48 V system: } \sigma_{\Delta\alpha_f} = 0.41 \text{ dB} \tag{3–27}$$

$$\text{60 V system } \sigma_{\Delta\alpha'_f} = 0.42 \text{ dB} \tag{3–28}$$

Before we combine the distribution of nominal RE_s and that of variations due to variations in the feeding system, we should envisage the fact that these distributions are of a different nature. The distribution of nominal RE_s relates to variations amongst subscribers, whereas deviations of the feeding system can to some extent also vary for each individual subscriber. The value of nominal RE_s for the subscriber concerned means a systematic influence on each telephone call; the effect of variations in the feeding system is more random. As to the systematic influence a special effect in the appreciation of the subscriber seems possible, namely he becomes either accustomed to systematic loud or weak calls, or he increasingly takes offence at the situation. We have no further information to what extent this possible psychological phenomenon occurs in practice, and no indication which of the two possibilities will dominate. Therefore, we will keep this complication in mind, but nevertheless combine the distributions. Taking into account the assumed variations in feeding systems, we find the values given in part B of Table 3.8 for our model network. The distributions are plotted in Figure 3.13.

The ultimate national distribution of sending reference equivalents depends on the proportion of subscribers served by either of the two feeding systems. The 48 V feeding

* We assume that practical tolerance limits correspond roughly to plus and minus three times the standard deviation of the distribution of variations.

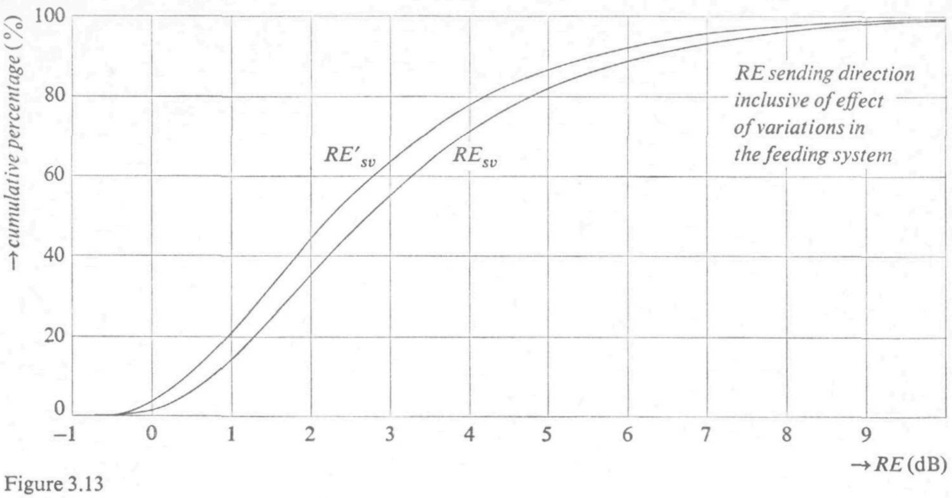


Figure 3.13

system is planned to become the standard system in the future, but it will take a rather long time before this will be realized completely. Today each system serves about 50% of the subscribers. So we have to combine the distributions of both systems in order to obtain an estimate of the national situation (part C in Table 3.8). The cumulative distributions are given in Figure 3.14.

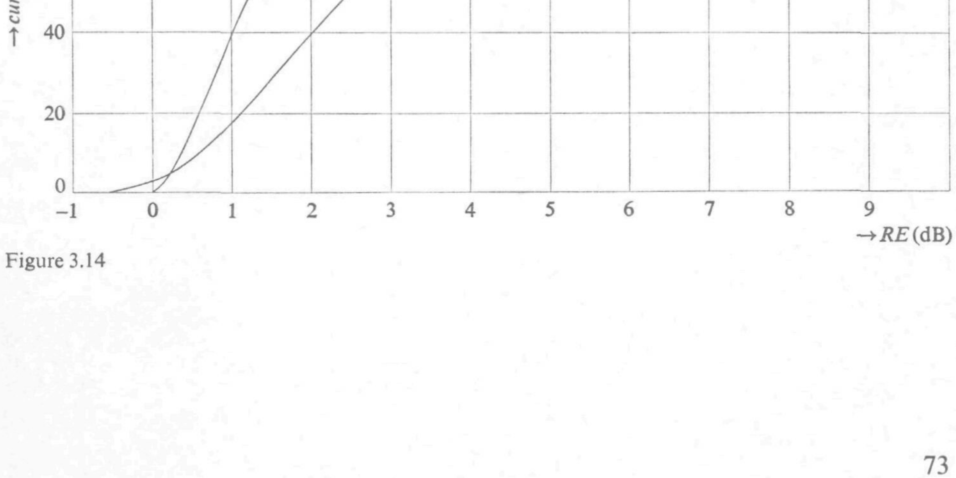


Figure 3.14

References Chapter 3

1 CCITT, Handbook *Local telephone networks*, Chap. V, p. 61 (ITU, Geneva,1968).

2 v. Zoest, W. H., v. Rooijen, M. F. and Mol, H., *Het telefoontoestel*. In: Het PTT-Bedrijf, I no. 4 (1948), pp. 113-132.

3 CCITT, Handbook *Local telephone networks*, Chap. V, p. 33 (ITU, Geneva, 1968).

4 Richards, D. L., *Telecommunication by speech*, p. 363 (Butterworths, London, 1973).

5 v. Hemert, R. and Kuin, J., *Automatische telefonie*, p. 12 (Vereniging van Technisch Hoger Personeel der PTT, 's-Gravenhage, 1968).

6 CCITT, Handbook *Local telephone networks*, Chap. V, pp. 61-62 (ITU, Geneva, 1968).

7 CCITT, *Ibidem*, Chap. V, pp. 62-63.

8 Richards, D. L., *Loudness ratings of telephone speech paths*. In: Proceedings of The Institution of Electrical Engineers, 118 no. 3/4 (1971), pp. 423-436.

9 Richards, D. L., *New definitions for loudness ratings*. In: Proceedings of The Institution of Electrical Engineers, 119 no. 10 (1972), pp. 1429-1441.

10 Sullivan, J. L., *A laboratory system for measuring loudness loss of telephone connections*. In: The Bell System Technical Journal, 50 no. 8 (1971), pp. 2663-2739.

11 Braun, K., *Theoretische und experimentelle Untersuchung der Bezugsdämpfung und der Lautstärke*. In: Telegraphen-Fernsprech-Funk-und Fernseh-Technik, 29 no.2 (1940), pp. 31-37.

12 Braun, K., *Ein neuer Bezugsdämpfungsmesser mit objektiver Erregung und Anzeige*. In: Telegraphen-Fernsprech-Funk-und Fernseh-Technik, 29 no. 8 (1940), pp. 223-227.

13 Mol, H., *Eigenschappen van koolmicrofonen*. In: Het PTT-Bedrijf, III no. 2 (1950), pp. 85-91.

14 Mol, H., *Theorie van de koolmicrofoon* (I). In: Het PTT-Bedrijf, III no. 4 (1951), pp. 128-134.

15 Means, D. R., *T1 carbon transmitter model for use in computer-aided analysis of telephone set transmission characteristics*. In: The Bell System Technical Journal, 54 no. 7 (1975), pp. 1301-1318.

16 de Jong, C. and Mugie, R. F. A., *Voedingsdempingen en niveauverschillen voor enkele voedingssystemen en typen koolmicrofonen*. Dr. Neher Laboratorium Memorandum nr. 12a TL, Nov. 1960.

17 v. Leeuwen, W. A., *Transmissietechnische aspecten van het telefoontoestel*, deel 3. Dr. Neher Laboratorium Memorandum nr. 256 TL (deel 3), Aug. 1968.

18 Bakker, C. and v. Leeuwen, W. A., *Transmissietechnische aspecten van het telefoontoestel*, deel 5. Dr. Neher Laboratorium Memorandum nr. 256 TL (deel 5), Sept. 1973, p. 35.

4 Reduction of variations in reference equivalents

4.1 *Acceptable values of overall RE; preferred range*

In the CCITT recommendations concerning the overall RE of international connections, the higher values and the allowable maximum have up to now been given ample attention. The obvious reason for this is that there was (and to some extent still is) a real risk of too weak calls. On the other hand, there is no recommendation for the minimum value of overall RE; only for the sending RE of the national part of an international connection a (provisional) minimum allowable value is recommended [1], in order to prevent overloading of transmission systems. However, within national networks many calls will be established between subscribers at short distances from each other, e.g. local calls and especially extension-to-extension calls inside a PBX network (see Figure 1.1b). Therefore, in national transmission planning attention should also be paid to the lower values of overall RE. So on the one hand there is the growing need of international and intercontinental calls of good quality urging to increase the sensitivities of the national system. On the other hand, higher sensitivities of the telephone sets will in many cases create the problem of too loud calls coupled with reduced intelligibility and poor subscribers' comfort, apart from possible problems of overloading transmission systems and increased crosstalk and sidetone. It will be clear that in this situation both ends of the range of values of overall RE, occurring in practice, need well-balanced attention.

In the past, the CCITT recommended an absolute maximum of 40 dB for the overall RE of international connections [2]. In the actual recommendations [1] a statistical approach is used, specifying only maximum values for the sending and the receiving RE of the national part of an international connection for 97% of all the actual calls. So in fact no absolute maximum has been given for the overall RE, which seems reasonable because statistics play an important part in the ultimate subscribers' opinion on transmission quality. In the case of international calls addition of the RE's corresponding to the specified 97% limits of two national networks already results in an overall RE of 33 dB, to which the losses of the intermediate international circuits and deviations from nominal values should be added. So the total can even be appreciably higher.

In the CCITT Handbook *Local Telephone Networks* [3] a favourable range of total RE of + 0 to + 30 dB is suggested, taking into account the effects of too low values of RE. However, it can easily be shown that such a range will not entirely satisfy the customers.

The question of the preferred range of overall RE has been the subject of several investigations, of which the results have been published. In 1942 Strecker and von Susani [4] reported on this subject. They found an optimum in subscribers' opinions at a value of overall RE of about 1 Np (1 Np = 8.7 dB). Although no range is recommended in view of practical possibilities and dependence on noise conditions, the authors indicate a possibly preferred range between about 1 and 2 Np and a tolerable range between 0 and 2.5 Np.

Williams and Wilson in 1959 [5] mentioned experiments carried out at the U.K. Post Office Engineering Research Station, which resulted in a preferred range of overall RE of about + 6 to + 18 dB. Moreover, a maximum desirable sensitivity corresponding to a minimum RE of 3 dB is quoted.

In 1963 Boeryd [6] published results of experiments with the object of determining the optimum attenuation for telephone connections. He suggests a range of overall RE extending from 0 to + 20 dB.

Kitchenn [7] presented curves with regard to the relationship between user's opinion and overall RE. These curves indicate a wide variation in opinion amongst the users. A minimum of adverse opinions occurs at an overall RE of about 9 dB. With this value there were still 1% opinions 'too loud' and 1% 'too faint'. A maximum for the opinion 'preferred' was found around 11 dB. Kitchenn sets a lower limit of about 3 dB for overall RE, in order to avoid overloading of transmission systems, and he investigates several possible ranges of overall RE. A range from + 4 to + 19 dB is mentioned as a most desirable objective, but not considered to be realistic, taking into account the practical situation.

In 1970 Munday [8] mentioned–together with the distribution of users' opinions as given by Kitchenn [7]–a range from + 6 to + 18 dB studied by the U.K. Post Office as a preferred range for planning purposes. Richards [9] gives other background information concerning this range, by presenting curves of subscribers' opinions in a similar way as Kitchenn did. Although the general tendency is the same, percentages of subscribers' opinions differ considerably. The results indicate that in the most favourable situation 60% of all subjects were completely satisfied. This was the case at an overall RE of 12 dB; at that value even about 20% of the subjects considered the connection to be 'too loud', whereas another 20% gave 'too quiet' as their opinion.

A Japanese contribution to the International Seminar on National Telephone Transmission Planning, Melbourne 1970 [10] mentioned a maximum RE of 17 dB in order to provide a 'desirable transmission quality of service'.

Within the CCITT Study Groups XII and XVI this point has recently been studied as well. In their 1974 meeting these Study Groups prepared a proposal for additions to the existing recommendations mentioned before. More details (median values) of the distributions of RE's of the national part of an international connection have been proposed [11].

In the proposed text for the revised recommendation the following sentence is found:

'Subjective tests have shown that the preferred range of nominal overall reference equivalents for telephone connections is 6-18 dB approximately with the preferred value in that range of about 9 dB'. This statement was also based on additional information from other sources than those mentioned above, namely a contribution from the USSR Telecommunication Administration [12] quoting a range from 7 to 18 dB for optimum values of overall RE, and a contribution from the American Telephone and Telegraph Company [13] indicating a preferred overall RE of approximately 9 dB. All this information shows that there is only a relatively small range of values of overall RE which offers a more or less optimum satisfaction to the users. Consequently it is important to limit ranges of RE occurring in practice as much as possible.

Addition on a random basis of the values of RE_s and RE_r as calculated in Table 3.8C, may give an idea of the contribution of subscribers' lines to the dispersion in overall RE. We calculate an overall standard deviation of 2.57 dB.

In Table 3.8 we noticed that with the various distributions of RE_s and those of RE_r the 5-95% and the 1-99% ranges correspond to about 3.1 σ and 4.7 σ respectively; the distributions concerned are fairly similar to a chi-square distribution with 4 degrees of freedom. The distribution of the sum of RE_s and RE_r will be more or less similar to a chi-square distribution with 8 degrees of freedom. For complete connections we also have to add the variations resulting from routing and variations of the circuits interconnecting the two subscribers' local systems. In that case the overall distribution of the RE will probably approach a gaussian distribution.

When we consider some theoretical distributions, we find the following results for the various ranges:

	5-95%	1-99%
chi-square distribution with 4 degrees of freedom	3.10 σ	4.59 σ
chi-square distribution with 8 degrees of freedom	3.19 σ	4.61 σ
gaussian distribution	3.29 σ	4.65 σ

So it appears that for our purpose the 5-95% and the 1-99% ranges can be estimated fairly accurately from the 3.2 σ and the 4.6 σ values respectively. Thus the calculated overall standard deviation of 2.57 dB will correspond to

$$\begin{array}{l} \text{a } 5\text{–}95\,\% \text{ range of about } 8.2\text{ dB} \\ \text{and a } 1\text{–}99\,\% \text{ range of about } 11.8\text{ dB} \end{array} \qquad (4\text{–}1)$$

We can conclude that compared with the preferred range of overall RE the subscribers' lines make a very important contribution to the spread in RE. Therefore it seems opportune to study possibilities of reducing the variation in the RE of subscribers' lines. It is clear in this respect that the sending RE should be examined first. Methods and means which suppress feeding loss could offer a considerable reduction of variation in RE. But also methods reducing or compensating the variations in line RE should be considered. In the following we shall study a number of possibilities which can be used

for this purpose. Attention will be given to the effect of tolerances in the system.
We shall restrict our considerations to solutions at voice frequencies using a conductor pair for each subscriber's line. In some national networks multiplex systems (both frequency and time division multiplex) are used under special conditions, e.g. a group of subscribers at an extremely large distance from the exchange [14,15]. In a way such solutions can be considered as moving the exchange towards the subscriber, because the input of the voice frequency connection to, and the feeding system for, the telephone set will be found at the end of the multiplexed line.

4.2 *Methods to reduce variations in reference equivalents*

4.2.1 *Suppression of feeding loss*

Feeding systems in combination with a carbon microphone as generally applied will produce feeding loss (see Section 3.4). In principle, however, it is possible to design a feeding bridge which supplies an almost constant current. This means that somewhere in the d.c. loop a current regulating device should be introduced. Such solutions have not found general application, although some forms of controlling feeding current within the feeding bridge were implemented, in the past [5] and more recently [16]. It is also possible to control feeding current within the telephone set. This type of control has been applied in the form of manual insertion of fixed resistors in series with the line during the installation of the set, or more recently in the form of automatic regulation of the feeding current [17]. In some cases, devices in the telephone set designed to control the sensitivity dependent on line current, also influence the d.c. current to some extent, thus reducing the feeding loss [18, 19].
Another, and probably more promising, possibility is the use of a different type of microphone with a sensitivity basically independent of feeding current. Modern technology offers a wide range of types e.g. magnetic, electro-dynamic, piezo-electric, electret, etc. [20]. But all these microphones offer a sensitivity which is considerably lower (some dozens of dB's) than that of a modern carbon microphone. So, if replacement is considered, an amplifier is indispensible. Fortunately transistors and integrated circuits offer excellent opportunities. The gain of the amplifier can be made almost independent of feeding current by a well-considered design, making use of negative feedback. At the moment, stable microphones with built-in amplifier, completely compatible with carbon microphone insets can be manufactured [21] and are already used in some foreign networks in special situations [22] or in a field trial [23]. In another national network a stable microphone with separate amplifier has since 1967 been used in the standard telephone sets [24]. It seems the moment is not far away when overall introduction of stable microphones will no longer be prohibitive from an operational and economic point of view.
With such a type of stable microphone the influence of the line current on the char-

acteristics of the telephone set can be eliminated almost completely. This will also have some effect on the values of line RE as calculated in Section 3.7 due to the elimination of the variation in the impedance of the set. Moreover, in Chapter 5 it is proposed that the impedance of the telephone set be changed, for reasons of stability and echo, into a value of 600 Ω. This will require changes within the set. It seems realistic to consider the combined effect of both changes, i.e. a new microphone and a new impedance. So we have to determine the RE of subscriber's lines between 800 Ω (at the local exchange) and 600 Ω, using the method of Section 3.2. For several cable types the

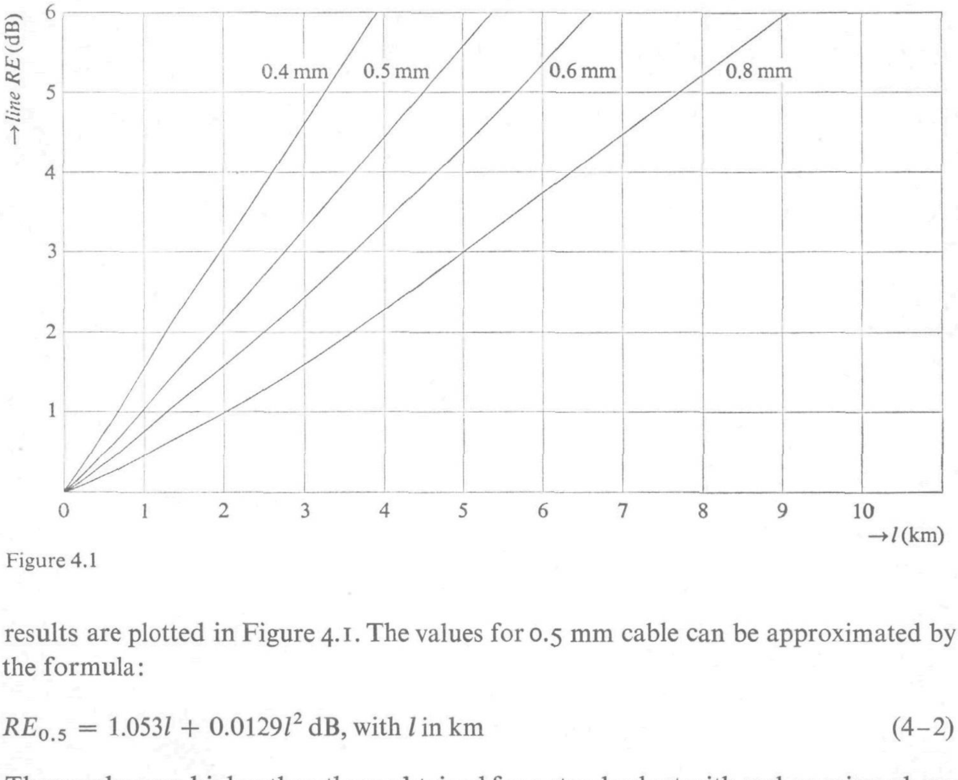


Figure 4.1

results are plotted in Figure 4.1. The values for 0.5 mm cable can be approximated by the formula:

$$RE_{0.5} = 1.053l + 0.0129l^2 \text{ dB, with } l \text{ in km} \tag{4-2}$$

These values are higher than those obtained for a standard set with carbon microphone and inductive impedance; compare formula (3–18). Two factors contribute to this increase. Firstly the favourable effect of the current dependent impedance is absent, although this effect is very small (see Section 3.7). The major proportion of the increase is caused by the change from the inductive and frequency dependent impedance of the telephone set into a resistive impedance of 600 Ω. This results in somewhat lower values of insertion loss at lower frequencies, but in higher values at higher frequencies. The ultimate effect is an RE which is 0.7 dB higher for 5 km 0.5 mm cable (see also Table 5.13).

With the help of formula (4–2) we can calculate the distribution of the line RE in the model network. We find for sending and receiving:

$$\mu_{RE} = 1.98 \text{ dB and } \sigma_{RE} = 1.44 \text{ dB} \qquad (4\text{–}3)$$

These values are independent of the feeding system, as long as the feeding current is within the limits for a proper functioning of the microphone amplifier. Compared with the results in Table 3.8C there is some increase in the values of RE for the receiving direction, but a considerable reduction for the sending direction. For the sum of RE_s and RE_r, added on a random basis, we find a standard deviation of 2.04 dB, corresponding to

$$\begin{array}{l} \text{a } 5\text{–}95\,\% \text{ range of about } 6.5 \text{ dB} \\ \text{and a } 1\text{–}99\,\% \text{ range of about } 9.4 \text{ dB} \end{array} \qquad (4\text{–}4)$$

These values mean an improvement with regard to those given by (4–1) of slightly more than 20%. It should be noted that in these figures the effect of eliminating the feeding loss is to some extent cancelled by the increased insertion loss due to the 600 Ω impedance of the set. If we had used a constant impedance equal to Z_{to} (see Section 3.6), the standard deviation for the sum of sending and receiving RE would have been 1.84 dB, corresponding to

$$\begin{array}{l} \text{a } 5\text{–}95\,\% \text{ range of about } 5.9 \text{ dB} \\ \text{and a } 1\text{–}99\,\% \text{ range of about } 8.5 \text{ dB} \end{array} \qquad (4\text{–}5)$$

Now the improvement over the values of (4–1) is near to 30%.
Considering the ranges of RE, it is worth noting that the stable microphone will not show the instability and large tolerances inherent in carbon microphones. The additional dispersion in values of RE caused by these effects, which was not included in the values of Table 3.8C, will also disappear.

4.2.2 *Reduction of line losses*

A next step, of course, is to study possibilities of further reduction of variations in line RE by lowering the insertion loss of the subscribers' lines. The simplest manner of reducing this loss is to increase the diameter of the conductors in order to decrease the loop resistance. An additional favourable effect is a decreasing feeding loss if carbon microphones are still being used. But it is evident that for economic reasons this solution offers very limited possibilities. In practice, application is restricted to special situations, such as extreme long lines, falling outside the normal planning rules [25]. Another, quite obvious solution is to apply loading coils to subscribers' lines. In fact this solution has found practical application in several national networks, but is generally restricted to very long lines [26] or special conditions e.g. long lines serving a large PBX with long extension lines. The limited application stems from the fact that insertion of simple loading coils will only bring about a reduction of insertion loss at the higher frequencies. Consequently the reduction of RE is rather limited. A more significant reduction could be obtained by applying more coils together with matching transformers, which is expensive. However, not only costs seem to have precluded general application of loading, but also a number of practical problems, such as restrictions on spacing between loading coils, deviating impedance, limitation of flexibility in cross-connection points, etc. Although the application on very long lines only, will offer some reduction of the ranges of RE values of subscribers' lines, both for sending and receiving, the ranges for the overall RE of complete connections, comprising the majority of these connections (e.g. 90%) will only be influenced slightly.

A primitive form of loading is obtained by the use of a terminating impedance with an inductive component (see Paragraph 4.2.1). However in Chapter 5 it will be seen that, for reasons of stability and echo, only a small inductive component is acceptable. The resulting reduction in line RE is small; for 5 km of 0.5 mm cable only about 0.2 dB (see Section 5.7, Table 5.13).

4.2.3 *Insertion of supplementary loss*

It is possible to reduce the variation in values of RE by inserting additional loss in the connection in the form of a resistive pad or an artificial line. Depending on the loss of the subscriber's line, additional loss of an appropriate value is inserted, in order to keep the total RE more or less constant. In practice this pad or artificial line can be installed at the subscriber's premises (e.g. in a connection box) or in the local exchange. The first solution in a simplified form is used in the network of the Federal Republic of Germany. Here for short lines (loop resistance smaller than 250 Ω) an additional pad has been installed at the subscriber's premises [27, 28]. The principal drawback of such a solution is that the equipment is not identical with all subscribers, but will depend on the prevailing circumstances. Moreover, changes in the network, e.g. new cables, new exchanges, rerouting, etc. will often require replacements at the subscriber's premises and this is hardly possible in practice. The whole system requires special planning and attention and asks for a skilled maintenance staff [29]. Therefore, for operational reasons, many administrations consider such a solution as undesirable. These practical problems can partly be solved if the pads are installed in the local exchange. Here the equipment is easily accessible to the maintenance people, although within existing exchanges there will in most cases not be sufficient room and technical facilities to install the additional networks. An inevitable consequence of this solution is that all sets have to be equipped with sensitive transmitters and receivers, because in actual networks the general problem is to reduce the RE on longer lines in order to obtain acceptable values for long-distance and international calls. On the other hand it is necessary to prevent too loud calls on short lines.

Operational problems can further be reduced by inserting the required additional networks into the connection within the local exchange, under the control of the switching equipment. In this way a considerable reduction in the number of networks can be obtained, because the networks are only inserted into connections in which, and as long as, they are actually wanted. Hence the networks can be used with a much greater efficiency.

In practice this solution could only be used in processor-controlled exchanges, and even then sufficient room should be available to install the pads and sufficient capacity in the processor memory is required to store the criteria on the subscriber's lines. In such a system changes can very conveniently be effected by simply introducing new data into the processor memory. This solution will be applied in Western Germany in the new processor-controlled switching system EWS 1 to insert an additional pad for short subscribers' lines [22]. As only recently a start has been made with the introduction of processor-controlled exchanges in the networks, this possibility offers only a long-term solution.

In the cases mentioned above, the number of different classes of pads or artificial lines has for practical reasons to be limited and the aim of a constant RE for subscribers' lines will only partly be achieved.

4.2.4 *Regulation by grouping of transmitter and receiver insets*

A similar effect as described in Paragraph 4.2.3 is obtained by adapting the sending and receiving sensitivity of telephone sets to the loss of the subscriber's line. To limit the range of different sensitivities a system of grouping is necessary. In practice only a very small number of classes is manageable. Such a system of grouping was and is still being used in Western Germany [27, 28, 29], although there is a tendency to reduce the original number of classes (three) and to equip by far the greatest majority of subscribers with standard transmitter and receiver insets [22].

This system of grouping has all the operational disadvantages mentioned in Paragraph 4.2.3.

4.2.5 *Automatic continuous regulation in telephone sets*

Operational problems can also largely be prevented by the introduction of an automatic sensitivity control which is dependent on line current in the telephone sets. This solution has found ample application all over the world [5, 18, 19, 23, 30]. There are many ways in which the regulation can be realized. This depends for example on the type of hybrid circuit used in the set [31]. Generally the regulating devices contain voltage dependent resistors (varistors) of the passive type, in combination with a carbon microphone.

All regulating devices introduce additional loss, which is reduced at smaller line current (= longer line), the transmitters and receivers being of rather high sensitivity. It is general practice to use different regulating characteristics for sending and receiving.

This type of regulation shows the fundamental drawback that the regulating action is not controlled direct by line loss, but by line current. A first consequence is that the regulation depends on the feeding system, and is affected by variations in this system. Here a fundamental problem arises in PBX's. It is usual in the Netherlands that the extensions receive their feeding current from a feeding bridge within the PBX itself. Thus for extension-to-extension calls the regulation basically functions correctly and this is indeed sorely needed in order to prevent too loud calls on these usually very short lines. But for calls from and to the public network the regulation is incorrect because it does not take account of the line loss between the local exchange and the PBX. Special provisions within the PBX are required to solve this problem, e.g. additional measures to adapt the feeding current for incoming and outgoing calls.

Another problem exists in networks not using a uniform conductor gauge for all subscribers' lines. In that case there is not an unambiguous relationship between RE and loop resistance, as can be seen in Figure 4.2, where the values of RE from Figure 4.1 are

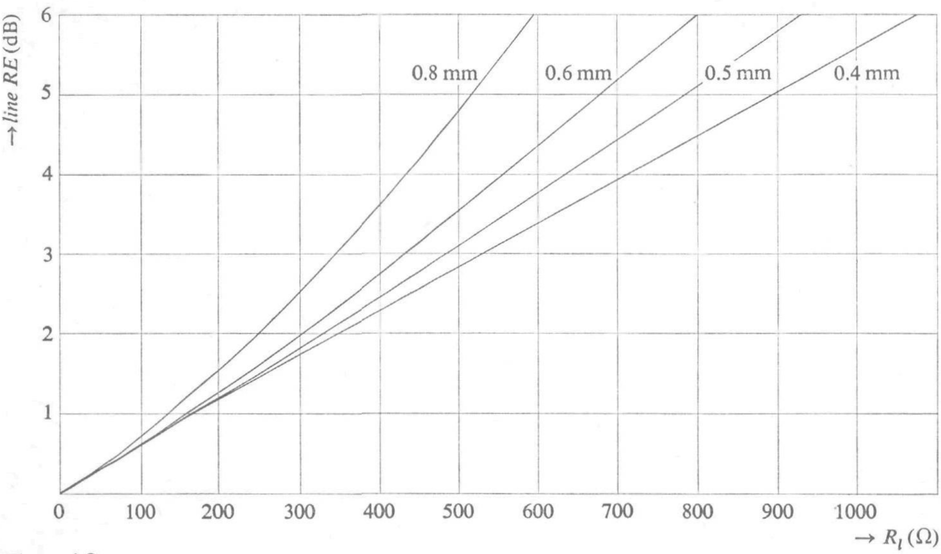


Figure 4.2

given as a function of loop resistance. These curves show that for the diameters which are most frequently used (0.4, 0.5 and 0.6 mm) the loop resistance is to a large extent decisive of the value of RE. The use of a regulator based on the values corresponding to 0.5 mm will only result in a relatively small error in regulating action.

It is worth noting that regulating circuits in the telephone sets will, for reasons of costs and reliability, in general only contain a very limited number of components. In practice regulating characteristics, even with nominal values of the components, present a compromise and in general only give a rough approximation of what was wanted [5, 17, 18, 19, 29, 30]. Moreover, tolerances on values of components with variable characteristics are generally relatively large, whereas stability (e.g. with temperature) is rather poor, which is a disadvantage, particularly for subscribers' sets, operating under uncontrolled environmental conditions.

4.2.6 *Regulated additional loss in the local exchange*

A similar regulation as described in the preceding paragraph can be obtained by the installation of regulating circuits in the local exchange. A fundamental advantage is that in this case both d.c. line voltage and line current are available, which offers the possibility to use the loop resistance (including the d.c. resistance of the telephone set) as a criterion for the regulation. Consequently, the dependence on the properties of the feeding system could be eliminated. Also the environmental conditions are generally much more favourable than those inside telephone sets. Moreover, the number of devices needed can be reduced considerably by introducing the regulating circuits not in each individual subscriber's line, but inside the exchange after a first reduction stage. This reduced number presents the opportunity of paying more attention to accuracy.

Here again a problem arises with PBX's. The regulator now basically functions correctly for calls between the public network and the PBX, except for the additional (usually small) losses introduced by the PBX and the extension line. However, for the important class of extension-to-extension calls, additional loss inside the PBX will be required to prevent too loud calls.

As far as we know, the system of introducing automatic regulated loss in the local exchange has not found practical application, although the potential possibilities have been outlined by de Jong [32].

4.2.7 *Regulated gain in the local exchange*

The same effects as described in Paragraph 4.2.6 can be obtained by a gain-controlled amplifier in the local exchange. One of the drawbacks with passive regulators, namely the forced equality of the regulating characteristic for both directions of transmission (see Paragraph 4.3.5), will disappear. On the other hand, problems may arise with regard to the stability of this two-wire repeater which at least imposes restrictions on the minimum loss of line and repeater together. Therefore, in practice, this solution is restricted to long lines. The Rural Electrification Administration in the USA reported on the application of a repeater with gain control dependent on loop resistance for lines in rural areas [33]. The total attenuation of line and repeater together is maintained at a value of about 5 dB. An alternative method of providing automatic regulation was also indicated, namely switching the gain in steps.

Another application of gain in the local exchange is used in the Bell network for long subscribers' lines [14, 34]. In combination with measures to safeguard signalling and to increase feeding voltage, gain is introduced by the 'Range Extender with Gain'. For reasons of crosstalk the gain is restricted to 6 dB. There is no automatic regulation, the gain being adjusted manually. The equipment is installed in each subscriber's line involved. A similar application is envisaged for long lines in France [35]. The system uses a negistor in combination with a special telephone set, which can operate with small feeding currents.

4.2.8 *Automatic regulation by step-adjustable loss*

The problem of tolerances and instabilities of regulating components in telephone sets (see Paragraph 4.2.5) can probably be overcome by replacing the continuous variable loss by a range of fixed losses switched under control of the line current. It seems possible to reduce the deviations from the nominal value of the inserted loss in this way. On the other hand, new errors creep in, because the required continuous regulating characteristic is only approximated by steps. In this respect the resulting effect is the same as with grouping of insets or pads (see Paragraphs 4.2.3 and 4.2.4). The regulation remains sensitive to variations in the feeding system and to the effect of non-uniform conductors in the network. As far as can be ascertained, this possibility has not been applied in practice.
This method can also be used for regulation of additional losses or gain in the local exchange (see Paragraphs 4.2.6 and 4.2.7).

4.2.9 *Speech level control in the telephone set*

Problems with too loud calls could also be solved by preventing too high levels of received speech. This could be effected by automatic speech level control in the sets, which means that speech-controlled attenuation is introduced such that beyond a certain input signal level the output level is limited to an almost constant value. Wilson [36] discusses different systems and experimental circuits, but costs are considered to preclude general application. Only recently a practical application was reported in Bell Laboratories Record [37]. For extremely long lines, where even the gain which can be introduced in the exchange (see Paragraph 4.2.7) is not sufficient, a special handset has been developed which supplies additional gain by means of two built-in amplifiers, one for each direction of transmission. Too loud received speech, for example from extension sets, is prevented by a speech level controlled a.g.c. The system also provides control of the sidetone by reducing the receive gain in talking conditions. It is clear that in such systems the additional loss is not only dependent on the loss of the subscriber's line, but also on the loss of the chain beyond the local exchange and even on the speech level of the partner at the other end. So the relation to the subscriber's line is only an indirect one. The operate and release time of the regulating circuit can affect the transmission performance. For the present cost prospects are not very promising because rather complex active circuits are required.

4.2.10 *First evaluation of possibilities*

We shall briefly examine the potential possibilities of the most promising methods of reducing the variation in RE, mentioned in the preceding paragraphs.

– A stable microphone with built-in amplifier (Paragraph 4.2.1) offers a realistic possibility to eliminate the feeding loss, and hence to restrict the range of the RE.
– Automatic continuous regulation in the telephone set (Paragraph 4.2.5), as applied in several networks elsewhere, seems to offer a potential solution, apart from problems with PBX's. The same applies to automatic continuous regulation of loss (Paragraph 4.2.6) or gain (Paragraph 4.2.7) in the local exchange. But the accuracy of such types of automatic regulation, including the effect of variations in the feeding system, needs critical consideration. This will be done in a following section.
– For practical reasons the use of heavier gauge conductors or the application of loading coils (Paragraph 4.2.2) is to be restricted to special situations.
– The system of installing additional pads at the subscriber's end or in the local exchange (Paragraph 4.2.3), needs some closer consideration as concerns the effect of the very limited number of different pads possible in practice. Similar effects occur with grouping of insets (Paragraph 4.2.4) and with automatic regulation by step-adjustable loss (4.2.8). The effects on the accuracy of the regulation will be studied in Section 4.4.
– Speech level control in the telephone set (Paragraph 4.2.9), for the near future, only seems to offer a possible solution in extreme situations.

4.3 *Results with automatic continuous regulation*

4.3.1 *Ideal regulator; effect of feeding system*

To calculate the results which can be obtained by continuous regulation of the RE, some assumptions need be made. We assume a model network (see Section 2.9) with 0.5 mm conductors in which an automatic regulator controlled by the d.c. line current is inserted in each subscriber's line, either in the telephone set or in the local exchange. The characteristics of the regulator are assumed to be ideal, which means that the relationship between the additional loss of the regulator and the line current, with a nominal feeding system, is such that the total RE of the subscriber's line, the regulator and the telephone set is the same for all subscribers. This applies to sending as well as receiving. In practice, the d.c. characteristics of regulators can show a considerable variety, depending on the type of regulator components and the type and circuit diagram of the regulator. In our calculations we shall take into account a total voltage for the regulator and the telephone set with a constant value of 6 V in the d.c. loop. This arbitrary, but–with a view to practice–reasonable assumption will only have a rather small influence on our results.

In the first instance we shall consider the situation that a stable microphone is used in the telephone set and that the impedance of this set is 600 Ω (see Paragraph 4.2.1). With these assumptions we can calculate the effect of variations in the feeding system on the regulating action.

We introduce an equivalent loop resistance R_{eq} (as was done in Section 3.5), being the value of the loop resistance in a nominal feeding system which leads to the same value of the line current as in the situation under consideration. Variations in the feeding system are indicated by v and r (see Section 3.5). For the calculations use can be made of Figure 3.5, whereby the circuit of the telephone set is replaced by a constant voltage of 6 V. We find:

$$\frac{V_b(1+v)-6}{R_l+R_b+r} = \frac{V_b-6}{R_b+R_{eq}} \quad or \quad R_{eq} = \frac{(V_b-6)\,(R_l+r)-vV_bR_b}{V_b-6+vV_b}$$

Substitution of a new parameter $v' = \dfrac{vV_b}{V_b-6}$ results in

$$R_{eq} = \frac{R_l+r-v'R_b}{1+v'}\,\Omega \quad \text{or} \quad R_{eq} \approx R_l + r - v'(R_l+R_b)\,\Omega \qquad (4\text{-}6)$$

For 0.5 mm conductors ($R_l = 174\,l$) with the help of formulas (4–2) and (4–6) the deviation from the required regulating characteristic can be calculated, under the assumption that deviations are relatively small. The result is:

$$\Delta RE \approx -(6.05\,10^{-3} + 8.6\,10^{-7}R_l)\,\{r - v'(R_l+R_b)\}\,\text{dB}$$

For the model network the standard deviation of the resulting variation in RE can be calculated, assuming that variations r and v' in the feeding system have a mean value 0 and a standard deviation of s_r and $s_{v'}$ respectively:

$$\sigma^2_{\Delta RE} = 40.1\,10^{-6}\,s_r^2 + 53.1\,s_{v'}^2 \qquad (4\text{-}7)$$

In order to obtain some idea about the values to be expected in practice, we insert for the variations in the feeding system the values mentioned in Section 3.9, i.e. $s_r = 70\ \Omega$ and $s_v = 0.035$, which corresponds to $s_{v'} = \dfrac{48}{48-6}\,0.035 = 0.040$. The resulting standard deviation is:

$$\sigma_{\Delta RE} = 0.53\,\text{dB} \qquad (4\text{-}8)$$

For a regulating circuit designed for a 60 V feeding system and operating in sets connected to such a feeding system, formulas (4–6) and (4–7) are valid as well. In that case we assume as concerns the variations in the feeding system (see Section 3.9):

$s_r' = 85\,\Omega$ and $s_{v'}' = \dfrac{60}{60-6}\,0.035 = 0.039$. Now we find:

$$\sigma_{\Delta RE'} = 0.61\,\text{dB} \qquad (4\ 9)$$

This result shows that the effect of equivalent variations in the 60 V system is larger than in the 48 V system. This can be explained from the fact that in the 60 V system the line current is to a larger extent determined by the properties of the feeding bridge than with the 48 V system.

4.3.2 *Effect of non-standard conductors*

As can be seen in Figure 4.2, the use of non-standard conductors will result in inaccurate regulation. To obtain an impression as to which deviations can be expected in a real network, this effect was studied for the subscribers' lines included in the survey (see Chapter 2). The resulting deviation in RE was calculated for these lines, taking into account an ideal regulator designed for 0.5 mm conductors. It turned out that the mean value of the errors was very small (0.02 dB). A standard deviation of 0.18 dB was calculated. As it is to be expected that in the present and the future telephone system the proportion of deviating conductors will decrease (see Paragraph 2.8.2), we can conclude that the influence will be small, at least compared with the other effects discussed above.

4.3.3 *Influence of limited range and tolerances of regulators*

We have to envisage the fact that regulating circuits are highly unlikely to offer ideal characteristics. First of all it is rather unrealistic to assume that the RE's of all subscribers' local systems could be increased to the maximum occurring in the network. This would result in such a high mean value of these RE's that it is not acceptable in a reasonable transmission plan, unless the sensitivity of the telephone sets is increased considerably, which would give rise to problems with respect to crosstalk and sidetone. Anyhow, it means that for the majority of the subscribers' sets a considerable amount of additional (regulated) loss would have to be inserted. The tolerances and stability of practical regulator components are rather poor and with higher values of loss inserted by the regulator, this will be more noticeable. Moreover, the range over which values of regulator components can be varied is rather limited. In practice, therefore, the regulating action will be restricted to a limited range of RE and even in this range the regulation will be far from ideal. The influence of these limitations will be studied.

For that purpose we assume that in the model network for lengths of up to a certain value l_o the nominal regulating characteristic is ideal, but that the actual loss introduced by the regulator shows a dispersion around the nominal value. The standard deviation of the relative deviations from the nominal loss is assumed to be constant for all values of additional loss introduced by the regulator. In lines with a length equal to or greater than l_o there is no additional loss.

On these assumptions the resulting variations in RE can be calculated. For a telephone set with a stable microphone in the model network the mean value and standard deviation of the total RE of line and regulator are plotted against the value of l_o in Figure 4.3. The standard deviation of the relative variations around the nominal values of regulator loss (expressed in percentages) is indicated as a parameter in Figure 4.3b. The latter diagram clearly shows that in the case of rather inaccurate and unstable components, the regulating action should be limited to part of the complete range of lengths occurring in the network only. Descriptions of regulated sets showing practical results

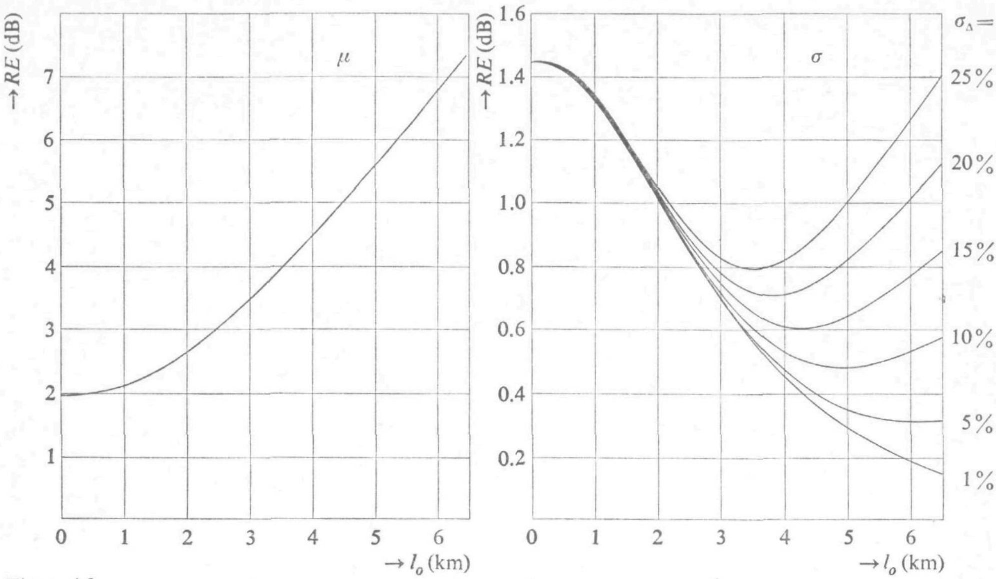


Figure 4.3 a. b.

illustrate this point [5, 17, 18, 29, 30].

As a consequence of the limited range of regulation the effect of variations in feeding systems will be somewhat reduced. However, as the proportion of subscribers not falling inside the regulating range will be relatively small, this reduction will be of secondary importance.

4.3.4 *Automatic regulation in telephone sets*

From a practical point of view it is interesting to consider the possibility of installing only one standard type telephone set (with regulator) throughout the whole network, notwithstanding the fact that two different feeding systems are in general use. With an eye to the future the standard set should be equipped with a regulator designed for use in a 48 V feeding system. The regulating errors occurring if such a set is used on subscribers' lines with a 60 V feeding system can easily be calculated. Again an equivalent loop resistance is calculated, now representing the value of the loop resistance in a nominal 48 V system, leading to the same feeding condition. The result is:

$$R_{eq'} = -22 + 0.778\,\{R_l + r - v'\,(R_l + 1000)\}\,\Omega \qquad (4\text{–}10)$$

As could be expected the regulation is imperfect, even without variations in the feeding system. In that case the equivalent loop resistance is: $R_{eo'} = -22 + 0.778\,R_l\,\Omega$. For the corresponding distribution of errors in the model network we find:

$$\mu_{\Delta RE_o'} = 0.59\text{ dB and } \sigma_{\Delta RE_o'} = 0.34\text{ dB} \qquad (4\text{–}11)$$

The standard deviation of the additional variations resulting from variations in the feeding system is given by:

$\sigma^2_{\Delta' RE'} = 23.6\ 10^{-6}\ s_r'^2 + 42.8\ s_{v'}'^2$

With $s_r' = 85\ \Omega$ and $s_{v'}' = 0.039$: $\sigma_{\Delta' RE'} = 0.49$ dB.

Thus the total standard deviation becomes: $\sigma_{\Delta RE'} = 0.59$ dB (4–12)

This value is smaller than the result obtained with a circuit specially designed for the 60 V system, see formula (4–9). This can be explained by the following reasoning (which is also applicable to a 48 V system). If we make the regulator less effective, so that variations in RE resulting from differences in line length are only partly compensated, this results in a decreasing influence of variations in the feeding system. However, a regulation error (which was 0 with an ideal regulator) will occur, which also contributes to the total standard deviation. As addition of both contributions is on a power basis, a minimum value of standard deviation will be obtained with a regulator which is somewhat less effective than the ideal regulator. The extent to which the regulating action should be reduced to obtain the minimum standard deviation of resulting variations, depends on the variations in the feeding system. With the variations in the feeding system assumed by us, the required reduction in regulating action is about 10%. It is wise to keep this effect in mind when designing a practical regulating circuit; unavoidable deviations from the ideal characteristic are preferably to be such that too much regulating action is precluded anyhow.
Now we return to the results obtained with a regulating circuit designed for a 48 V system but operating with a 60 V feeding system. Formula (4–11) shows that on an average the values of the resulting RE are 0.59 dB higher than with a 48 V feeding system. In a network where each of the two feeding systems serves about 50% of the subscribers, this means an additional contribution to the standard deviation of the total RE, which now becomes:

$\sigma_{\Delta RE} = 0.63$ dB (4–13)

Of course, with smaller variations in the feeding system than assumed, this standard deviation of the resulting RE will be smaller. But it will not approach 0, because even with ideal feeding systems the standard deviation will be 0.38 dB, owing to the fact that one standard telephone set (with regulator) is used in a network where two feeding systems are in operation.
In telephone sets with a carbon microphone feeding loss should also be compensated for the sending direction, which results in a more complex regulating circuit. The required effect can be obtained by regulation of the transmitter feed current or by additional regulation in the four-wire part of the transmission circuit in the set; combinations of both are possible as well. So for the sending direction the loss introduced by the regulating circuits is considerably higher than for the receiving direction (with

a 48 V system about 1.6 times) and therefore the effect of a limited regulating range and the inaccuracy of regulator components will be correspondingly larger, but relatively similar to that described in Paragraph 4.3.3.

As far as the effect of variations in the feeding system is concerned, we can note that with a system of line current controlled regulation the line current determines both the loss of the regulator and the sensitivity of the carbon microphone. Thus, with an ideal regulator the compensation of feeding loss will be complete at each line current, irrespective of the way in which this current was obtained. Consequently, the type of feeding system and variations in the feeding system have no influence on the compensation of the feeding loss. However, a limited regulating range (see Paragraph 4.3.3) will mean that with longer lines not only the nominal feeding loss variations are uncompensated, but also the variations resulting from variations in the feeding system. On the other hand, the feeding system on these lines cannot influence the regulation (because there is no regulating action at all). So we can estimate that the ultimate effect of variations in the feeding system will not differ much from the results calculated in Paragraph 4.3.1.

Finally, it should be realized that large tolerances are inherent in carbon microphones. This applies in particular to the resistance of the microphone, which affects the line current and as a result the regulation accuracy of line RE.

4.3.5 *Automatic regulation in the local exchange*

It is to be expected that a regulator installed in the local exchange will be adapted to the feeding system used in this exchange. So the problem caused by two feeding systems being used in the network, and the resulting variation in RE if only one type of standard telephone set is used in the network, will disappear.

A regulator with passive components, inserted in the two-wire transmission path of the local exchange, does not offer the possibility of different characteristics for the two directions of transmission. If the telephone sets are equipped with carbon microphones the regulation for the sending direction will be imperfect, unless additional measures in order to suppress feeding loss are taken in the d.c. loop (see Paragraph 4.2.1). This means more complicated regulator circuits, which could be avoided if stable microphones are used.

As indicated in Paragraph 4.2.6 the regulator in the local exchange could in principle be controlled by the loop resistance (inclusive of the resistance of the telephone set). So there are possibilities of improving the accuracy of the regulation over that obtainable with regulators in the telephone sets, also because the environmental conditions in the local exchange are usually controlled more satisfactorily.

But still the accuracy of regulator components will not be ideal, and the range of regulation will be limited as well. So the problems indicated in Paragraph 4.3.3 will remain, although perhaps to a smaller extent than is the case with regulators in the telephone sets.

4.3.6 *Discussion of results*

The conclusion of the foregoing considerations in this section is that a number of influences affect the accuracy of automatic continuous regulation. These influences are:

a variations in feeding systems

b presence of two different feeding systems in the network

c deviating conductors for subscribers' lines

d necessary limitation of regulating range

e inaccuracy and instability of regulator components

It can be estimated that, as a result of all these effects, automatic regulation in telephone sets will in practice reduce the standard deviation of the distribution of the RE of the subscribers' local systems by only a factor 2 to 3. If regulators are installed in the local exchange better results can be obtained, depending on how much effort is spent on improvements at the points *a*, *b* and *c* mentioned above.

4.4 *Step-adjustable regulation of RE*

4.4.1 *General*

With this type of regulation the regulating action is obtained by insertion of additional loss in one or more steps of a fixed value. The basic criterion on which it is decided to introduce a certain step is the RE of the subscriber's line. The insertion can be effected manually (grouping of insets, pads at the subscribers' premises or in the local exchange) or automatically (under control of the exchange processor). In these cases the decision which of the fixed values of additional loss should be inserted is based on data on the subscriber's line and is in principle made once for all.

The additional loss can also be switched into the connection automatically, as the switch is controlled direct by the line current or the loop resistance. The switch is operated at fixed levels of the controlling quantity. The proper functioning depends on the relationship between this quantity and the line RE. Now problems may arise with non-standard conductors and with variations in the feeding systems. On the other hand, it can be expected that the accuracy of the loss of fixed pads, including the switch, can be much better than with a continuous regulator.

Irrespective of the way the loss is inserted, in all the cases mentioned above, with an ideal system (i.e. a system not affected by deviations) the resulting effects are essentially the same. In the following we shall study the effect of such systems with step-adjustable regulation.

4.4.2 *Ideal system with one step*

In all systems the number of possible steps will, for practical reasons, be very limited. Therefore, firstly, a system with only one step will be studied. In such a system an additional loss of a fixed value a_o dB is added to all subscribers' lines with an RE smaller than a predetermined value. In an ideal network with only one type of conductors this value of RE can easily be translated into a fixed length l_o. The issue is how optimum values for a_o and l_o can be determined. One way would be to consider the range of values of RE which occur in the network and to take the middle of this range. Then the corresponding length is l_o and the value of a_o is equal to half the width of the original range of RE. With this system the range of RE is halved.

In our model network the range of RE is, in principle, unlimited at the upper end; so the rule indicated above cannot be applied straightaway. But it could be applied to, for example, the 5-95% range (see Sections 3.9 and 4.1). For this purpose we shall consider the situation that the telephone sets are equipped with stable microphones so that variations in RE of the local system are equal for sending and receiving, and regulation for both directions of transmission can be effected in the two-wire path. In this situation the RE of the subscriber's line is given by formula (4-2). Then in our model network the 5% value is 0.34 dB and the 95% value 4.78 dB. In order to reduce the 5-95% range as much as possible, it is necessary to insert an additional loss of $a_o = \dfrac{4.78 - 0.34}{2} = 2.22$ dB in all lines with an RE lower than $\dfrac{4.78 + 0.34}{2} = 2.56$ dB, which corresponds to a length $l_o = 2.36$ km. The resulting distribution of RE can be calculated; the values for mean and standard deviation are: $\mu = 3.60$ dB and $\sigma = 0.89$ dB. As the probability density has been neglected, it is questionable whether this is the optimum solution.

We can also try to find the minimum value of the standard deviation of the RE, which

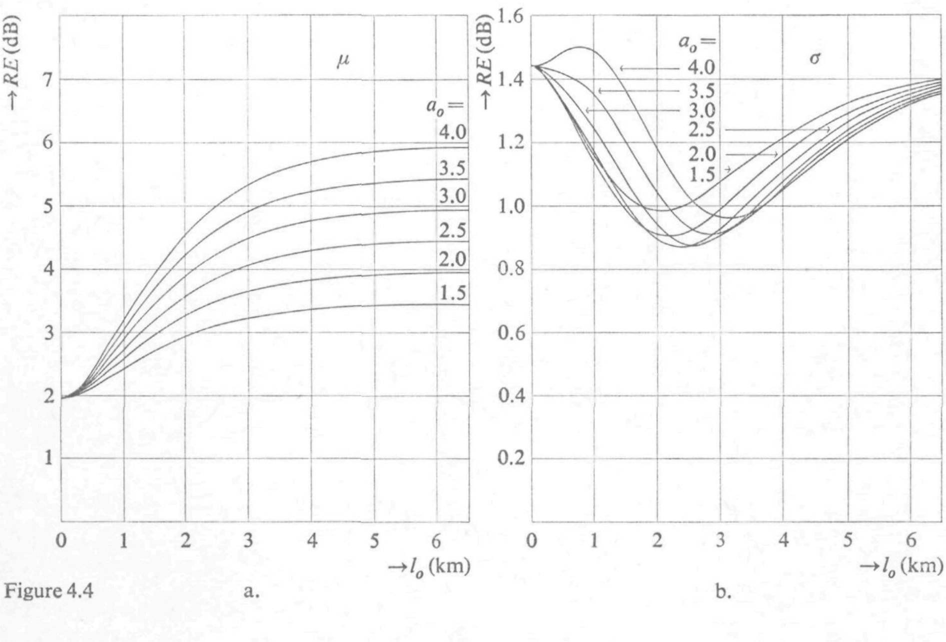


Figure 4.4 a. b.

seems a better approach from a statistical point of view. For the model network we then find: $a_o = 2.63$ dB and $l_o = 2.42$ km. For the resulting distribution of line RE: $\mu = 3.95$ dB and $\sigma = 0.87$ dB. These results differ only slightly from those obtained by halving the 5-95% range. The resulting standard deviation is somewhat more than half the original value of 1.44 dB given in formula (4–3).
In Figure 4.4 the values of mean and standard deviation of the resulting distribution of RE are for several values of a_o plotted against the value of l_o. In Figure 4.5 cumulative

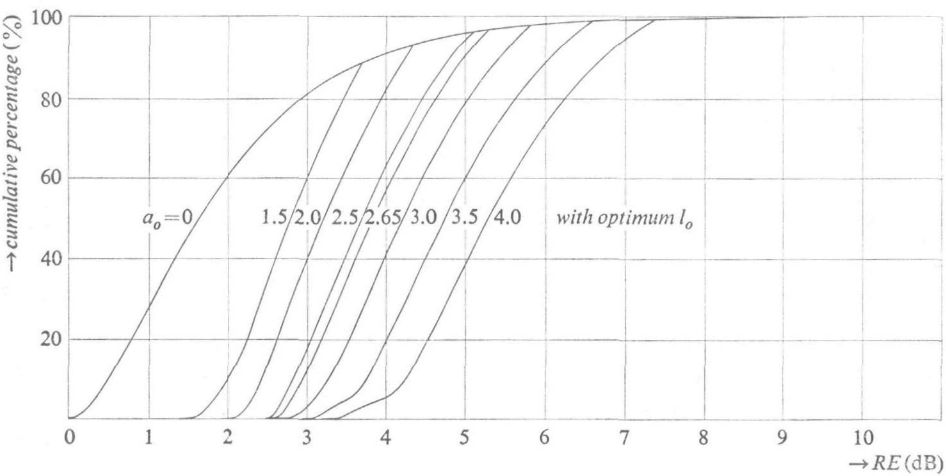


Figure 4.5

distribution curves are plotted for a range of values of a_o. For each curve the value of l_o was chosen so as to give the minimum value of standard deviation.
Figure 4.4b clearly indicates that the minimum for the standard deviation is rather flat, which means that the choice of a_o and l_o is not very critical. On the other hand the mean value (Figure 4.4a) changes considerably with l_o at values around the optimum.

4.4.3 *Effect of variations in feeding system on automatic regulation*

Of course the feeding system will have no influence on regulation in a manual system (e.g. grouping of insets) or in a processor-controlled system. If, however, the switching is controlled by line current, the actual line length at which the switching is accomplished will be affected by variations in the feeding system. And this will influence the ultimate distribution of RE, as can be deduced from Figure 4.4. Calculations on the influence of variations in the feeding system can be made, using a method more or less similar to the one of Section 4.3. The results show that, in a model network, with the optimum conditions mentioned above ($a_o = 2.63$ dB, $l_o = 2.42$ km) and with the same assumptions as made in Paragraph 4.3.1, the variations in a 48 V feeding system give rise to an additional contribution to the standard deviation of RE given by:

$$\sigma^2_{\Delta' RE} = 28.2\ 10^{-6}\ s_r^2 + 42.1\ s_{v'}^2$$

With $s_r = 70\ \Omega$ and $s_{v'} = 0.04$ we find: $\sigma_{\Delta' RE} = 0.45$ dB. Compared with the result found for continuous regulation (formula 4–8)), there is only a minor reduction.
When we consider the situation that this step-adjustable regulating circuit designed for optimum functioning in a 48 V system is connected to a 60 V system, it is clear that the results will deviate from the optimum. Under nominal feeding conditions we find $\mu = 4.30$ dB and $\sigma = 0.97$ dB in this case. The additional influence of variations in the feeding system is given by:

$$\sigma^2_{\Delta' RE'} = 8.54\,10^{-6}\, s_r'^2 + 21.1\, s_{v'}'^2$$

With $s_r' = 85\,\Omega$ and $s_{v'}' = 0.039$: $\sigma_{\Delta' RE'} = 0.31$ dB.

In a national network with two types of feeding systems each serving about 50 % of the subscribers, general application of a standard regulating system based on the 48 V feeding system, will result in a distribution of the total of line RE and additional loss (inclusive of the effect of variations in the feeding systems) with $\mu = 4.12$ dB and $\sigma = 1.01$ dB.

4.4.4 *Regulation if sets are equipped with carbon microphones*

The type of regulation described above can also be applied if the sets are equipped with carbon microphones. In that case different characteristics are required for the two directions of transmission, which can be achieved in several ways: changing the d.c. conditions of the microphone or switching additional loss in the four-wire part of the set, or a combination of both. The method applied will have some influence on the resulting distribution of RE, owing to the complicated relationship between d.c. conditions and feeding loss (see Section 3.4). But the ultimate result will be rather similar to the results indicated in Figures 4.4 and 4.5, however with correspondingly higher values for sending RE.
Apart from the additional variations resulting from the instability and large tolerances of carbon microphones, we have to consider the effect of variations in the feeding system. It can be expected that the effect of these variations on feeding loss will be compensated to some extent by the influence on the value of l_o; under conditions resulting in an increased feeding loss (corresponding to a smaller feeding current), the actual length up to which the additional loss is inserted, will be smaller. A more detailed consideration of this effect shows that the compensation is far from complete. So the influence of variations in the feeding system cannot be neglected. It should be noted that the partial compensation only occurs in automatic systems with switching controlled by line current. In manual or processor-controlled systems of regulation the complete influence of variations in the feeding system on feeding loss (see Section 3.5) should be taken into consideration.

4.4.5 *Regulation with more steps*

The accuracy of the regulation can, of course, be improved by increasing the number of steps in additional loss. It is clear that if the number of steps is very large the results will more and more approach those of continuous regulation (see Section 4.3). As a first improvement we shall study a system with two steps. Again the question is how to choose the values of the steps and the lengths at which they are switched. For a system with a stable microphone and values of RE in accordance with formula (4–2), we determined those values leading to a minimum standard deviation of resulting RE in a model network. These values are given in Table 4.1, together with the corresponding values of mean and standard deviation.

Table 4.1

Length	0–1.69 km, additional loss	4.21 dB
	1.69–3.57 km	2.57 dB
	> 3.57 km	0 dB

$\mu = 5.21$ dB, $\sigma = 0.63$ dB

Compared with the results calculated in Paragraph 4.4.2 for a system with one step, the improvement in standard deviation is not very impressive: 0.63 dB instead of 0.87 dB.

Concerning the influence of variations in the feeding system we can expect values between those found for a system with one step (Paragraph 4.4.3) and those for continuous regulation (Paragraph 4.3.1), which were already close together.

A further decrease in standard deviation of RE can be obtained by adding an extra step to the regulating system. For the model network the values resulting in a minimum standard deviation were once more determined. The results are given in Table 4.2. We see that the improvement in standard deviation per extra step becomes smaller at a higher number of steps, as was to be expected. Therefore, in practice the number of steps will be very limited.

The distribution of RE resulting from a step-switched regulated system will show a rather irregular shape, as can be seen in Figure 4.5 for a system with one step. In a

Table 4.2

Length	0–1.34 km, additional loss	5.31 dB
	1.34–2.59 km	4.09 dB
	2.59–4.38 km	2.54 dB
	> 4.38 km	0 dB

$\mu = 6.13$ dB, $\sigma = 0.49$ dB

system with a limited number of steps the regulating action does not extend to long lines, because the contribution of these lines to the standard deviation of RE is obscured by their relatively small number. The result is that for a minimum standard deviation the lengths at which steps are switched, are located in the range of lengths with a high probability density, as can be seen in Tables 4.1 and 4.2. However, it may be useful to apply special measures to very long lines, e.g. longer than 4.5 or 5 km, being only a few per cents of the total (see Section 2.3). Otherwise, subscribers with such long lines will experience systematically unfavourable transmission quality. Moreover, signalling and feeding conditions often require special measures as well. The additional measures for this special group of subscribers could easily be incorporated in a system with step-switched regulation; in the system with three steps, the last step was already switched at a rather great length, i.e. 4.4 km (see Table 4.2).

In systems in which the switching is controlled by the line current there is an important influence of tolerances in the feeding system. Then even more than two steps seem unrealistic, particularly in the case the regulating circuit has been installed in the telephone set.

4.5 *Critical consideration*

We now shall review the methods described and the results calculated in the preceding sections of this chapter, also taking into consideration such practical operational points as compatibility with existing equipment, possible impact of PBX's, etc.

Replacement of the carbon microphone in the telephone sets by a stable microphone with a built-in amplifier will eliminate feeding loss. This solution can be made compatible with the existing feeding and signalling systems, and even with the existing transmitter insets, so that introduction in the network can easily be effected by replacement of insets. Practical experience with operation in existing networks has shown that such a solution is feasible. Cost prospects are hopeful. Additional advantages are the more stable characteristics of the microphone and improved quality of speech.

Manual regulation of RE in the telephone sets or at subscribers' premises (e.g. grouping of insets or installation of additional pads) is not considered a realistic solution because of practical and operational problems.

From Sections 4.3 and 4.4 it can be concluded that automatic regulation in telephone sets, of either the continuous or step-adjustable type, is considerably affected by variations in the feeding systems. Moreover, for other practical reasons (tolerances and instability of component values, limited range, etc.) such an automatic regulation can only partly compensate variations in RE. Besides, for an important category of calls, namely those from and to PBX extensions, the regulating system in the sets does not give the required effect, unless additional measures have been provided in the PBX. PBX's also lead to problems if automatic regulation has been provided in the local exchange. However, now the additional measures required in the PBX are uniform and independent of the position of the PBX in the local network. Automatic regulation in the local exchange offers opportunities for a better accuracy and a more efficient use of the regulating circuits. However, the ultimate result continues to depend on the relationship between d.c. conditions and the RE of the subscriber's line.

Calculations showed that step-adjustable regulation, with a rather small number of steps, already offers a reasonable reduction of variations in RE, taking into account all other variations involved in the complete speech path.

A system of processor-controlled step-adjustable regulation in new exchanges seems to offer attractive prospects. The number of different classes of subscribers' lines can be small, and the additional equipment can be used with greater efficiency than is possible with equipment installed individually per line. For the class of longest lines it may also be possible to insert additional gain (e.g. by means of a negistor), which offers the advantage that the sets need not be very sensitive; such very sensitive sets could cause problems with crosstalk and sidetone. If gain for the longest lines is included in a system with two steps (three classes of subscribers' lines) no additional provisions are needed for an important group of subscribers; only the class of short lines requires additional loss. Processor-control of the switching in this system offers such a flexibility as is highly desired from an operational point of view. Alterations, for example those resulting from changes in the subscriber's line plant, can easily be accomplished. It is clear that such a system can only be realized in new processor-controlled exchanges, and requires adequate provisions in the switching equipment and in the processor.

Concerning the time needed for a large-scale realization of the measures proposed in a practical network, we can conclude that a stable microphone can be introduced in a reasonable short period of time. The new microphone can not only be introduced in new sets, but also when replacing transmitter insets, which at present have a relatively short average life.

It is clear that the introduction of regulating circuits in telephone sets will take much more time, because of the much longer average actual life of telephone sets, compared with insets. There are, moreover, many forms of special telephone sets which cannot easily be replaced.

In practice, the introduction of regulation in exchanges, and particularly of the processor-controlled system, can only be realized in new, and specially designed exchanges. So this is a solution on longer term.

4.6 *Conclusions*

In order to meet the subscribers' preference in a more satisfactory way, it is desirable to reduce the variations in RE resulting from variations in subscriber's line length, found in the present telephone network.

Surveying the possibilities to reduce the dispersion of RE, as discussed above, we can conclude that replacement of the carbon transmitter by a stable microphone with amplifier offers a good possibility to reduce the range of RE. Such a new microphone could be introduced within a relatively short time, because it can be made compatible with the existing systems. Moreover, stabler operation and higher speech quality can be achieved. Further reduction of the variations in RE can be obtained by some form of automatic regulation. Automatic regulation in telephone sets, controlled by the line current, will only be a partial solution. The introduction of this automatic regulation will take a rather long time, because replacement of at least the transmission circuit in the telephone sets is required. This introduction should, therefore, only be considered if strictly necessary. Automatic regulation in the local exchange, controlled by the line current or a combination of line current and voltage, may give a greater degree of accuracy, but this can hardly be introduced in existing systems.
On longer term a solution with more promising prospects will be a system of processor-controlled switching of additional provisions in the local exchange. Especially a system with a fixed value of additional loss for short subscribers' lines and gain for (very) long lines seems to be an attractive solution. In this system, only rather simple additional measures are required in PBX's, i.e. uniform additional loss for extension-to-extension calls inside the PBX network. It seems at least justified to take this possibility into consideration when designing new processor-controlled exchange systems.

References Chapter 4

1 CCITT, *Green Book*, Vol. III-1, Recommendations G. 111 and G. 121, pp. 13-16 and 32-38 (ITU, Geneva, 1973).
2 CCITT, *Red Book*, Vol. III, Recommendation G. 111, p. 5 (ITU, Geneva, 1961).
3 CCITT, Handbook *Local telephone networks*, Chap. V, p. 7 (ITU, Geneva, 1968).
4 Strecker, F. and v. Susani, G., *Untersuchungen über den günstigsten Bereich der Bezugsdämpfung im Fernsprechverkehr*. In: Elektrische Nachrichten Technik, 19 no. 11 (1942), pp. 241-252.
5 Williams, F. E. and Wilson, F. A., *Design of an automatic sensitivity control for a new subscriber's telephone set*. In: Proceedings of The Institution of Electrical Engineers, part B, Vol. 106 (1959), pp. 361-371.
6 Boeryd, A. *Some reactions of telephone users during conversation*. In: Ericsson Review, 42 no. 1 (1964), pp. 51-58.
7 Kitchenn, R. G., *Telephone transmission objectives*. In: The Telecommunication Journal of Australia, 18 no. 1 (1968), pp. 15-27.
8 Munday, S., *A survey of the transmission plans of the United Kingdom Post Office*. In: International Seminar on National Telephone Transmission Planning, Melbourne 1970, Vol. 1, Seminar papers, pp. 1.24-1.65.

9 Richards, D. L., *Telecommunication by speech*, pp. 280-281 (Butterworths, London, 1973).
10 Sumida, T. and Minami, T., *Introduction of four-wire switching system in toll centers in Japan*. In: International Seminar on National Telephone Transmission Planning, Melbourne 1970, Vol. 1, Seminar papers, pp. 2.1-2.17.
11 CCITT, *Study Group XII, Munich meeting*, 2-11 october 1974, Document COM XII-No. 69 (period 1973-1976), pp. 3-6.
12 USSR Telecommunication Administration, *Determination of optimal and limiting values of reference equivalents for international trunk and local networks*. Delayed contribution F, CCITT Study Group XII, Munich 1974.
13 American Telephone & Telegraph Cy, *Reference equivalent of national systems in the international transmission plan*. CCITT document COM XII-No. 41 (period 1973-1976).
14 Andrews, F. T., *Customer lines go electronic*. In: Bell Laboratories Record, 50 no. 2 (1972), pp. 59-64.
15 Spencer, H. J. C. and Kingswell, L. W., *The application by the British Post Office of carrier techniques in the existing local distribution network*. In: International symposium subscriber loops and services, Ottawa 1974, Conference Record, pp. 4.5.1-4.5.10.
16 Ortvad, A., *Principles of an automatic rural exchange for 1500 subscribers with electronic control circuits*. In: Teleteknik, English edition, Vol. X (1966), pp. 50-55.
17 Person, J. W., *Autorégulation des postes téléphoniques*. In: Commutation et Électronique, no. 44, Jan. 1974, pp. 75-84.
18 Kolbe, R. J., *The type 801 telephone*. In: The Telecommunication Journal of Australia, 13 no. 6 (1963), pp. 434-439.
19 Boeryd, A., *Transmission characteristics of the DIALOG*. In: Ericsson Review, 41 no. 4 (1964), pp. 147-161.
20 Quaiser, W., *Fernsprechmikrofone–ein Überblick über den Entwicklungsstand verwendbarer Wandlerprinzipien*. In: Der Fernmelde-Ingenieur, 26 no. 3 (1972), pp. 1-26.
21 Martin, E. and Müller, E., *Fernsprech-Piezomikrofon Ts 71*. In: Siemens Zeitschrift, 46 no. 4 (1972), pp. 207-209.
22 Dehmer, S. and Wirz, H., *Contribution of the Federal Republic of Germany*. In: International Seminar on National Telephone Transmission Planning, Melbourne 1970, Vol. 1, Seminar papers, pp. 3.1-3.18.
23 Guyer, P., *Telephonapparate Modell 70*. In: Technische Mitteilungen PTT, 50 no. 10 (1972), pp. 433-444.
24 Wangensteen, H. and Wessel, T., *DIALOG with microphone amplifier and tone ringing*. In: Ericsson Review, 44 no. 3 (1967), pp. 2-14.
25 CCITT, *White Book*, Vol. V, Suppl. 7, pp. 50-51, National network (Netherlands) (ITU, Geneva, 1969).

26 CCITT, *Ibidem*, Suppl. 7, pp. 11-16, North-American Network.
27 Bergmann, K., *Lehrbuch der Fernmeldetechnik*, p. 69 (Schiele & Schön, Berlin, 1973).
28 CCITT, *White Book*, Vol. v, Suppl. 7, pp. 51-55, National Network (Federal Republic of Germany) (ITU, Geneva, 1969).
29 Ebel, H. and Hörner, O., *Dämpfungsausgleich im Fernsprechteilnehmernetz und in Nebenstellenanlagen*. In: Informationen Fernsprech-Vermittlungstechnik, 4 no. 1 (1968), pp. 57-62.
30 Bennet, A. F., *An improved circuit for the telephone set*. In: The Bell System Technical Journal, 32 no. 3 (1953), pp. 611-626.
31 Hörner, O. and Langsdorff, W., *Übertragungseinrichtungen des Fernsprechanschlusses*. In: Siemens Zeitschrift, 33 no. 8 (1959), pp. 479-486.
32 de Jong, C., *Ontwikkeling Nederlandse telefoonnet*. Dr. Neher Laboratorium Verslag no. 176 TL (deel 1), March 1963, pp. 12-14.
33 Brewer, M. L. and Marthens, A. H., *Rural subscriber physical loops*. In: International symposium subscriber loops and services, Ottawa 1974, Conference Record, pp. 6.2.1-6.2.8.
34 Burgiel, J. C. and Henry ,J. L., *REG circuits extend central office service areas*. In: Bell Laboratories Record, 50 no. 8 (1972), pp. 243-247.
35 Person, J. W., *Systèmes d'abonnees à courant reduit*. In: International symposium subscriber loops and services, Ottawa 1974, Conference Record, pp. 6.4.1-6.4.7.
36 Wilson, F. A., *Speech-level control in telephone instruments*. In: Proceedings of The Institution of Electrical Engineers, 114 no. 7 (1967), pp. 907-915.
37 Hawley, G. T. and Radosevich, A., *G 36 handset*. In: Bell Laboratories Record, 53 no. 7 (1975), pp. 288-294.

5 Optimum termination of subscribers' lines

5.1 *Introduction*

As explained in Sections 1.5 and 1.6 balance return loss in a four-wire connection is an important factor in transmission planning. The value of the balance return loss is mainly determined by the degree of impedance match between the impedance Z_B of the balancing network and the impedance Z_L of the two-wire line presented to the two-wire terminals of the four-wire terminating set (see Figure 5.1). More precisely, balance return loss at the terminating set is the transmission loss introduced by the terminating set between 'return' and 'go' path, reduced by the sum of the transmission losses introduced between two-wire and four-wire terminals for both directions of transmission [1]. Thus, balance return loss is also influenced by the impedances at the four-wire terminals [2].

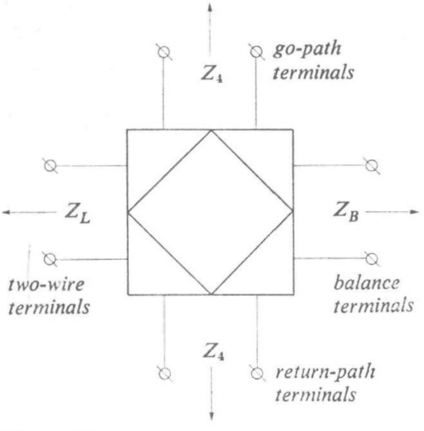


Figure 5.1

The usual form of terminating set is a hybrid circuit designed for the same nominal impedance at all four terminal pairs, and with the same loss for both directions of transmission. Assuming that transformers are ideal and that both paths of the four-wire circuit present the same impedance Z_4, the additional insertion loss introduced between 'return' and 'go' path is given by:

$$\alpha_b = -20\, log_{10} \left| \frac{Z_B - Z_L}{Z_B + Z_L} \left(1 - \frac{Z_4 - Z_L}{Z_4 + Z_L} \; \frac{Z_4 - Z_B}{Z_4 + Z_B} \right) \right| \text{dB}$$

Usually balance return loss is defined as [3]:

$$\alpha_r = -20 \log_{10} \left| \frac{Z_B - Z_L}{Z_B + Z_L} \right| \text{dB} \tag{5-1}$$

The latter formula represents only the actual additional loss between 'return' and 'go' path if $Z_4 = Z_L$ and/or $Z_4 = Z_B$. In practice, both conditions are usually sufficiently approached so that the simplified expression, formula (5-1), for the balance return loss can be used.

It is worth noting that this formula for the balance return loss, representing the additional loss introduced by the balancing conditions at the terminating set, is the same as the formula applicable to the normal concept of the return loss of the impedance Z_L against the impedance Z_B.

The impedance Z_L presented to the two-wire terminals of the terminating set in a practical network is determined by the properties of the two-wire line and of the impedance of the telephone set terminating this line (see Figure 1.1a.) These properties can vary considerably from call to call, and sometimes even during the call. It is clear that in a network with automatic switching it is impossible to adapt the balance impedance to each individual situation.* For practical reasons the balancing network has to be a compromise which, on an average, yields reasonable results. In this situation it is worthwhile studying the terminating conditions on subscribers' lines and considering to improve their influence on transmission performance.

The nominal impedance used in the Dutch telephone network has a value of 800 Ω (resistive). In 1964 de Jong published an article giving considerations as to the choice and basis of the nominal impedance in the network. A (translated) quotation: 'The construction of the Netherlands telephone network is most rigid in the lower network area.** In this area the characteristic impedance is 800 Ω. It is this impedance which is most suitable to serve as a basis for the whole network' [5]. In principle we support this conclusion, but would add that the image impedance of loaded cables (depending on the type of loading with or without matching transformer), as used for trunk junction circuits, approaches 800 Ω in part of the telephone band only. At higher frequencies in this band the impedance deviates appreciably from 800 Ω; owing to practical problems an impedance correcting network (m-derived section) has not found general application [6], although de Jong assumed that it would be introduced, which network was already referred to by Bast [7] in 1950. The correction network was also described in a CCITT Handbook [8].

* An automatic adaptation to the actual conditions could be obtained by means of an 'echo-canceller' [4], which uses correlation techniques to compensate the signal leaked across the terminating set. This method is still under development and requires complicated equipment. Because of the latter aspect this solution can only be considered for application in very long (and expensive) connections.

** This term indicates the part of the network between local exchange and the four-wire network, containing the 'trunk junction' circuits.

Unfortunately, the value of 800 Ω of the nominal impedance standardized all over the Netherlands network* deviates from the internationally standardized value of 600 Ω.** However, the impedance of 800 Ω has been used in the Dutch network for a rather long time already, and for reasons of compatibility it seems very difficult to introduce another nominal impedance value. The balancing networks at the four-wire terminating sets (see Figure 1.1a) are also based on 800 Ω. The standard design of this (compromise) network is a resistor of 820 Ω in series with a capacitor of 1 μF. 820 Ω differs slightly from the nominal value, because this value approaches the image impedance of loaded cables closer. The 1 μF has been provided partly because of the slightly capacitive behaviour of the image impedance of the cable, but mainly to compensate series capacitance usually inserted in the exchange between terminating set and cable.
The (resistive) nominal impedance does not in any way equal the characteristic impedance of the subscribers' lines. As is well-known, the expression for the characteristic impedance of a homogeneous line at speech frequencies can be approximated by

$$Z = \sqrt{\frac{R}{\mathrm{j}\omega C}} \quad \text{or} \quad Z = (1 - \mathrm{j})\sqrt{\frac{R}{2\omega C}} \tag{5-2}$$

where R represents the resistance and C the mutual capacitance per unit length. Therefore, the characteristic impedance is to a considerable extent frequency-dependent and capacitive.
The two-wire connection between the four-wire terminating set and the telephone set (see Figure 1.1a) can in principle be divided into two parts, namely:

a The trunk junction circuit between the four-wire terminating set and the local exchange. This circuit usually consists of loaded cable with an image impedance of roughly 820 Ω. Generally the terminating set is installed at the trunk switching centre (primary centre); in these exchanges the switching is often effected in the two-wire path. Some local exchanges will be installed in the same office as these primary centres and there will be no trunk junction circuit in the connection. In that case the value of 820 Ω of the balance impedance is particularly relevant to the terminating conditions of the subscribers' lines, because the matching between this impedance and the input

* It is worth noting that in principle it is not necessary to have the same nominal impedance in both the two-wire and the four-wire part of the network. Usually the terminating sets contain transformers which can easily convert the impedance. In other networks this has found practical application, e.g. North America [9], New Zealand [10] and South Africa [11]. However, practical reasons (measuring equipment, definition of levels, etc.) make it desirable to have the same nominal impedance throughout the network.

** An interesting point is that in the early days of international consultations the value of 800 Ω has for a number of years been provisionally recommended by the CCI for international circuits [12].

impedance of the subscriber's line now determines the value of the balance return loss almost direct.

The design of the two-wire exchanges usually found in the two-wire part of a connection (local exchange and often primary centre) is based on an impedance value of 800 Ω. In our study we shall consider these exchanges as incorporated in this part *a* of the connection. But we should bear in mind that the exchanges can cause appreciable deviations in impedance, because impedance tolerances for this type of exchange are rather large. In the present Dutch specification for local exchanges the requirement for the input impedance of an exchange terminated in 800 Ω is a lower limit of the return loss against 800 Ω of only 14 dB; at frequencies lower than 600 Hz this limit is even 10 dB.

b The subscriber's line (with a frequency-dependent impedance) between local exchange and subscriber's station. In our model network we assume uniform conductors of 0.5 mm (see Section 2.9). In the existing network other conductor diameters can be found, and some subscribers' lines can contain parts with different gauges (see Section 2.5). The characteristic impedance of these parts will be different, and there will be a reflection at the joint. A further examination shows that the return losses at such joints are rather high (0.4 mm against 0.5 mm: about 19 dB, and 0.6 mm against 0.5 mm: about 21 dB). The characteristics of a composite line can be reasonably well assessed by using the average cable parameters, as was done in Section 3.7 to calculate the insertion loss, although the approximation for the calculation of the impedances seen at the end of the line is less accurate than for insertion loss. We shall use the average parameters when considering the cables involved in the survey described in Chapter 2; these are indeed the only data available.

At the point where the parts *a* and *b* described above are interconnected, there is a major irregularity in impedance, which will give rise to reflection of signals. Table 5.1 gives values of return loss which can be expected.

Table 5.1

Frequency	Return loss against 820 Ω of the characteristic impedance of cables with conductors		
	0.4 mm	0.5 mm	0.6 mm
300 Hz	4.7 dB	5.6 dB	6.5 dB
500	5.8	6.8	7.4
1000	7.2	7.8	7.8
2000	7.9	7.5	7.0
3400	7.4	6.7	5.9

Important reflections can also be expected at the subscriber's end of the line, because usually the termination will not be completely matched to the characteristic impedance of the line. Reflections in the two-wire part of a connection will result in a reduced suppression of the transmission between the 'return' and the 'go' channel of the four-wire path. In this chapter we shall consider the possibilities of reducing the effect of these reflections.

5.2 *Matched terminations*

Regarding the prevention of major reflections the best solution would of course be interconnection of the trunk junction circuits and the subscribers' lines by means of impedance correcting networks, designed to have a correct image impedance at both sides. Of course, in this solution the subscriber's line ought to be terminated in its characteristic impedance at the subscriber's end. However, this–at first sight–simple and straightforward solution has a number of practical drawbacks, some of them will be considered here.

A major drawback of a network with the desired characteristics is that it will introduce considerable loss, which will amount to at least some 3 dB (see Annex A). Moreover, the subscriber's line is now terminated in its characteristic impedance at both ends; this leads to a higher insertion loss of the line than in the present situation or with some other terminations (see Table 5.13). Hence, the spread in the values of the line RE will be larger, which is unfavourable (see Section 4.1).

As far as stability and echo are concerned, only the impedance of the correction network presented to the junction circuit is relevant; in this respect there are no requirements as to the impedance at the other side of the correction network. This, however, would imply that generally the impedance of the subscriber's line presented to the subscriber's station will no longer be independent of the line length. This means that for the suppression of sidetone in the telephone set an important feature will be lost; then, in practice, for the suppression of sidetone only a compromise will be possible. Such a simplified correction network will have the same effect on the insertion loss of subscribers' lines as the network mentioned before, the spread in the RE will be larger.

The additional loss brought about by both types of correction networks, make these solutions unattractive, apart from such other practical problems as costs and the room required to install these rather complicated networks in the telephone system. Moreover, in practice it will be difficult to realize a termination with values corresponding to the characteristic impedance of the cable. With regard to practical measurements it is also a serious inconvenience that with this impedance the relationship between voltage (or current) and power level will be frequency-dependent.

The problems and inconveniences mentioned above make it understandable that, as far as we know, these solutions, although quite obvious from a theoretical point of view, have not found practical application. In [9] it is reported that for the North-American network the introduction was studied of a simple impedance correcting network, which introduces series-impedance between trunk junction circuit and subscriber's line at the higher frequencies in the telephone band (see also Paragraph 5.6.2). But apparently this application was not combined with a characteristic termination at the subscriber's end.

The considerations above indicate that it is desirable to study other, more suitable solutions.

5.3 *Effect of unmatched impedances*

If a completely reflection-free use of the subscriber's line, as described in the preceding section, is impracticable, the best solution would seem to reduce the number of points in a connection where major impedance irregularities occur, as much as possible. So we could be tempted to accept the reflection at the interconnection of the trunk junction circuit and the subscriber's line, but try to prevent the other major reflection by using a matched termination at the subscriber's end. However, the resulting values of return loss, which can be found in Table 5.1, are very low. Apart from the fact that a characteristic termination is impractical, it can easily be shown that for the situation concerned such a termination does not necessarily offer the best results. We consider a subscriber's line terminated in a resistance of 820 Ω. The reflections occurring at the interconnection with the trunk junction circuit and at the subscriber's end will now be opposite to each other. If the attenuation and the phase-change of the line are small, the reflections will for the greater part cancel and the desired reflection-free situation is approached, in spite of the two mismatch points in the connection.

It is clear that this consideration is less valid at higher frequencies (with corresponding higher values of attenuation and phase-change of the line) and also with longer lines. But in these cases the result could be improved by changing the terminating impedance such that the reflection generated at this point just compensates the other reflection.

In the telephone network we are only interested in the frequency range from 300 to 3400 Hz (see Section 3.2). At 3400 Hz a 0.5 mm cable shows per kilometre an attenuation of 2.2 dB and a phase change of about 0.27 radians. At 1000 Hz these values are 1.2 dB/km and 0.14 radians/km. As 50% of all subscribers' lines are shorter than 1.65 km (see Section 2.3) we can conclude that for an important proportion of all lines and in a large part of the telephone band an unmatched termination seems to offer the possibility of at least partial compensation of the two major reflections.

It is easy to calculate the terminating impedance causing complete compensation of the reflections. The input impedance Z_i of a line with length l, with characteristic impedance Z and propagation coefficient γ, and terminated in an impedance Z_e is given by:

$$Z_i = Z \frac{1 + \dfrac{Z_e - Z}{Z_e + Z} e^{-2\gamma l}}{1 - \dfrac{Z_e - Z}{Z_e + Z} e^{-2\gamma l}} \tag{5-3}$$

A reflection-free situation is obtained if this impedance equals the desired impedance Z_n (which in our case is 820 Ω). Then, the required terminating impedance will be:

$$Z_e = Z \frac{1 - \dfrac{Z - Z_n}{Z + Z_n} e^{2\gamma l}}{1 + \dfrac{Z - Z_n}{Z + Z_n} e^{2\gamma l}} \tag{5-4}$$

For several signal frequencies the values of this terminating impedance as a function of length of 0.5 mm cable were calculated for a desired input impedance of 820 Ω. The results are plotted in Figures 5.2a, b, c. These results show that this terminating impedance depends strongly on line length. At lower frequencies this can be explained by the dominating effect of loop resistance. So the required terminating impedance will about equal a resistance with a value of (820-174 l) Ω, which is in good agreement with Figure 5.2a.
Theoretically the terminating impedance could be made dependable on the line length by means of automatic line current controlled regulation, in a similar way as described for the regulation of RE in Chapter 4. Apart from all practical problems involved in such a regulation, Figures 5.2a, b and c show that for an important proportion of lines even a negative real part of the terminating impedance is required, so that this solution is unsuitable to be applied in practice.
From an operational point of view it is very desirable that one standard terminating impedance should be applied to all lines. In order to obtain some insight into the results which correspond to such a standard termination, we have, more or less arbitrarly, chosen the values corresponding to a complete compensation of reflections at a line of average length (1.85 km), for such a termination. The resulting return loss of the input impedance of the line against 820 Ω as a function of length is plotted in Figures 5.3a, b and c. At 300 Hz the results are very promising; they show that for a large range a good compensation of reflections is obtained (compare the value of 5.6 dB in Table 5.1). At 3400 Hz the return loss is for the majority of lines considerably better than the value of 6.7 dB found in Table 5.1. But very short and very long lines show results even slightly lower than this value. Apparently, the attenuation and the phase-change of the line play an important part at this frequency.
The results in Figures 5.3a, b and c show that at least for an important proportion of all subscribers' lines reasonable values of return loss can be obtained by means of a

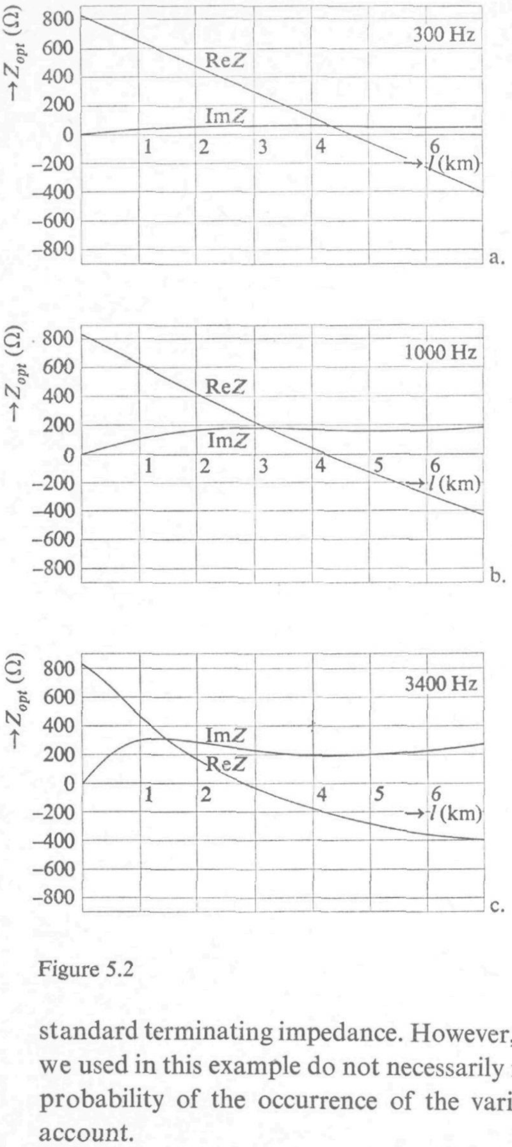


Figure 5.2

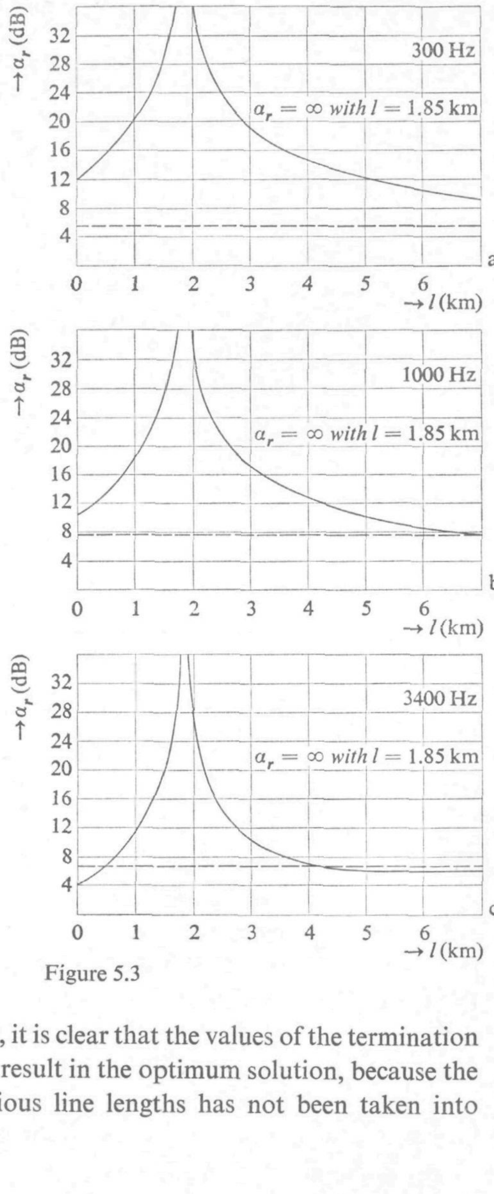


Figure 5.3

standard terminating impedance. However, it is clear that the values of the termination we used in this example do not necessarily result in the optimum solution, because the probability of the occurrence of the various line lengths has not been taken into account.

5.4 *Optimum standard terminating impedance*

5.4.1 *Choice of criterion; 'weighted return loss'*

The choice of one uniform terminating impedance for all lines necessarily involves a compromise. To be able to make the optimum choice we need a criterion representative of the quality of the terminating impedance from the viewpoint of echo and stability of complete connections.

A quantity generally used to indicate the quality and tolerance limits of terminating impedances is the return loss against the nominal impedance value. For our purpose the return loss of the input impedance of the subscriber's line at the local exchange against a reference impedance of 820 Ω (resistive) is relevant; the value of 820 Ω is a first approximation of the impedance of the two-wire network beyond the local exchange (see Section 5.1). The question is how the values of return loss corresponding to various line lengths can be weighted for their probability of occurrence and their relative importance as to echo and stability.

It is easy to decide that the worst case (i.e. lowest value of return loss, largest reflected signal) should not be taken as a criterion. Although this worst case can have some meaning from a viewpoint of stability, it is quite clear that probability plays a part as well, especially because many other statistical quantities codetermine the ultimate stability of a complete connection.

A usual method to take into account the probability density is to calculate the mean value (i.e. the first moment of the distribution). In this respect we would observe that for our purpose return loss is not a suitable quantity for the application of this method, because in an incidental case the value of the return loss might be extremely high. The mean value would be influenced disproportionally by this exceptional situation, whereas with regard to the risk of instability and objectionable echoes more attention should be paid to low values of return loss. Moreover, in the two-wire part of a telephone network there are as a rule several other points where more or less important reflections may be generated, which reflections will in practice largely reduce the favourable effect of very high values of return loss calculated at the input of the subscriber's line. Such sources of additional reflections could be considered to be: tolerances of cable parameters and terminating impedances, poor impedances of exchanges, difference between the reference impedance used in this study and the actual image impedance of loaded cables, mismatch at the terminating set between the image impedance of loaded cables and the (compromise) balance impedance, etc.

Many other variations are involved in the echo and stability path of a four-wire loop (see Figure 1.4), e.g. the number of four-wire circuits in cascade, variations of each circuit, correlation between variations for both directions of transmission, losses in exchanges, the balance return loss at the terminating sets which is in turn influenced by the loss of the trunk junction circuits.

Calculations concerning the stability of international connections made by the CCITT [13] show that especially for connections with a larger number of four-wire circuits (e.g. more than 4), which are most susceptible to instability, the standard deviation of balance return loss (in dB's) at the terminating set has only a minor influence on the safety margin against 'singing'. The mean value of the balance return loss (again in dB's), however, is found direct in the safety margin.

The above considerations apply to long and complicated (international) connections. For the relatively short national connections in the Netherlands, generally with a very limited number of four-wire circuits (the maximum is four [14],) the dispersion in the values of balance return loss is more important in stability considerations; the lower values are, of course, the most dangerous. With regard to the contribution of other additional reflections in the two-wire part (as indicated above), an addition of the magnitudes of all reflections might be appropriate from the viewpoint of stability.
CCITT calculations concerning echoes [15] show an even more reduced influence of the standard deviation of 'echo balance return loss',* because of an important additional contribution to the total of variations, made by the variation in subscribers' opinions (see Section 1.5). Here again the mean value of the echo balance return loss (in dB's) has a direct effect on the margins. If the contribution of the local system is predominating, e.g. in case the loss of the trunk junction circuit is very low, the mean value of return loss at the input of the subscribers' lines is meaningful. On the other hand, the rule for calculating the echo balance return loss indicates that for the effect on echo of several reflections an addition of the reflected power is appropriate. This places more emphasis on the mean reflected power of the local system whenever other contributions to the echo balance return loss play a more important part (which might occur if, for instance, the loss of the trunk junction circuit is close to the maximum of 3 dB).
From the above considerations it can be concluded that, as a measure for the quality of the input impedance of subscribers' lines, a weighted mean of the return loss is appropriate, with such a weighting as places more emphasis on lower values of return loss. This effect can be obtained if we take the mean value of the ratio of the amplitudes of the reflected and the incident signal, which ratio is given by the absolute value of the 'reflection coefficient', defined by the argument of the logarithm in formula (5-1). Thus, the contribution to the mean value resulting from reflections which correspond to low values of return loss is more pronounced, whereas the influence of reflections corresponding to high values of return loss is considerably smaller. Of course, if the power of reflected signals is used in the calculation of the mean value, these effects will be even more pronounced; in the light of the above considerations probably too much. Moreover, in one of the following paragraphs (Paragraph 5.4.3) it will be shown

* The CCITT provisionally defined as echo balance return loss the expression in dB of the unweighted mean of the power ratios of incident and reflected signal in the band of 500-2500 Hz [1]. For the calculation of the mean, a method is indicated in which the band is divided by five equally spaced ordinates and the trapezoïdal rule for numerical integration is applied. The frequency band and the way of weighting used (power ratio on a linear frequency scale) may be based on the special effect of echoes, although loudness could be expected to play an important part. The method differs in some respects from the one we used in the calculations of RE (Section 3.2); other aspects seem to be based on corresponding considerations. In many cases results of both methods of calculation will show only minor differences.

that the value of the optimum standard terminating impedance is not drastically influenced by the different types of weighting used to find the optimum.
For the purpose of this study we adopted, by way of a compromise, the mean of the absolute value of the reflection coefficient against 820 Ω at the input of the subscribers' lines, as a criterion for the quality of a standard terminating impedance at a given frequency. For the sake of convenience we shall express this mean value in terms of loss (dB) and we call it 'weighted return loss' ('$\bar{\alpha}_r$'), or in a formula:

$$\text{`}\bar{\alpha}_r\text{'} = -20 \log_{10} \{ \mathrm{E}\,[10^{-\alpha_r/20}] \} \tag{5-5}$$

where the symbol E [ ] indicates the 'mathematical expectation'.
We applied the above mentioned procedure to the situation in the Dutch telephone network and calculated the 'weighted return loss' for the model network with 0.5 mm conductors terminated in the impedance of the telephone set given by formula (3-17), reduced to:

$Z_{tl} = Z_{to} (1 + 0.021\, l)$ for 0.5 mm conductors.

The values of Z_{to} (impedance at zero line length) were derived from the same source as the one used in Section 3.6. The result for a series of frequencies is given in Table 5.2.

Table 5.2

Frequency	Impedance of telephone set	'$\bar{\alpha}_r$'
300 Hz	$(271 + j\,157)\ (1 + 0.021\, l)\ \Omega$	12.6 dB
500	$(309 + j\,229)\ (1 + 0.021\, l)$	12.8
1000	$(453 + j\,350)\ (1 + 0.021\, l)$	13.4
1500	$(543 + j\,382)\ (1 + 0.021\, l)$	13.2
2000	$(670 + j\,489)\ (1 + 0.021\, l)$	10.8
2500	$(825 + j\,503)\ (1 + 0.021\, l)$	9.3
3000	$(1021 + j\,495)\ (1 + 0.021\, l)$	7.8
3400	$(1159 + j\,418)\ (1 + 0.021\, l)$	7.1
echo		11.6

We also calculated the value of the return loss for echo by first applying weighting over the frequency band in accordance with the CCITT rule mentioned earlier in this paragraph. Secondly we weighted for probability density and for relevance in the way described for 'weighted return loss'. Thus we found a value for what could be called 'weighted echo return loss'; the result is given in the last line of Table 5.2.

5.4.2 *Curves of constant 'weighted return loss'*

A practical method to obtain insight into the influence of the terminating impedance on 'weighted return loss' is to consider a matrix of points on the complex impedance plane and to calculate, at a given frequency, the 'weighted return loss' for the terminating impedances corresponding to each of these points. By interpolation it is easy to find points with equal value of 'weighted return loss' and these points can be interconnected, so that a kind of curve of constant 'weighted return loss' is produced. As so many numerical calculations are required in this process, the use of a computer is indispensable.

This process will first be applied to the subscribers' lines in the survey (see Chapter 2). The results for some frequencies are given in Figures 5.4a, b and c.

Equivalent results can be obtained for the model network. Notwithstanding the approximation by simple formulas used in this case (see Section 2.9) the required result could not be found by analytical calculations, owing to the complex relationship between the input impedance of the line and its length (formula (5–3)). However, by means of numerical calculations the exact result can be approached as accurately as desired.

The results for the model network are given in Figures 5.5a, b and c. Comparison with the corresponding results in Figure 5.4 shows that there is a great resemblance. This is not astonishing because the average loop resistance in the survey deviated only slightly from the value corresponding to 0.5 mm conductors.

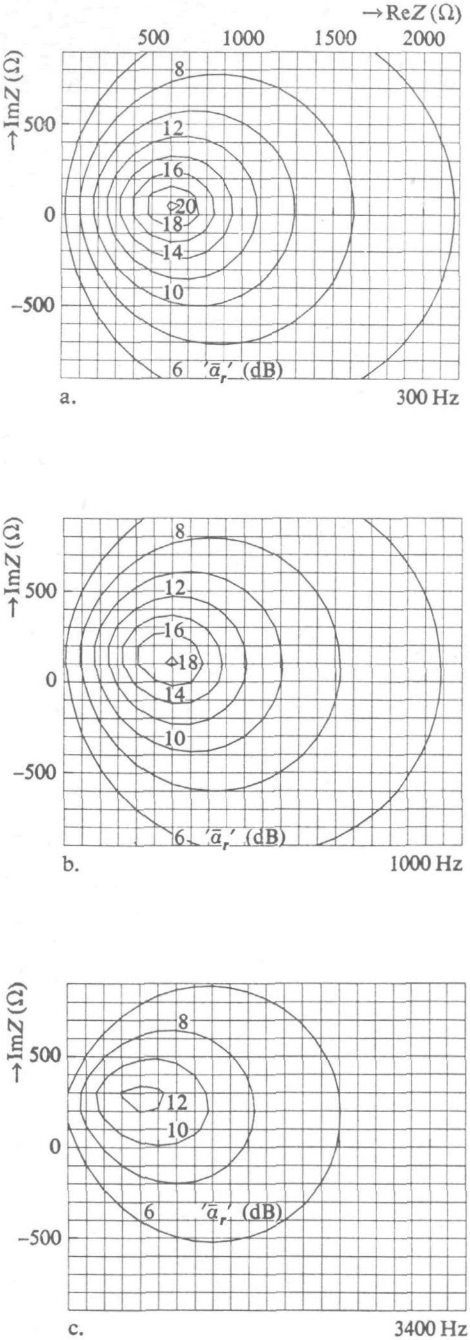
The curves of constant 'weighted return loss' show some resemblance to circles of constant return loss against a reference impedance [16], but they should not be confounded. The lastmentioned circles indicate impedances corresponding to a certain value of return loss against a reference impedance, whereas the other curves relate to impedances, which, if uniformly used as terminating impedance of subscribers' lines, give rise to a certain value of 'weighted return loss' against 820 Ω at the input of these lines.

5.4.3 *Optimum impedance*

For the subscribers' lines contained in the survey, as well as for the model network, the values of the terminating impedance yielding the maximum value of 'weighted return loss' can be determined at each frequency. The values for the 'optimum terminating impedance' found in this way are given in Table 5.3, together with the corresponding values of 'weighted return loss'.

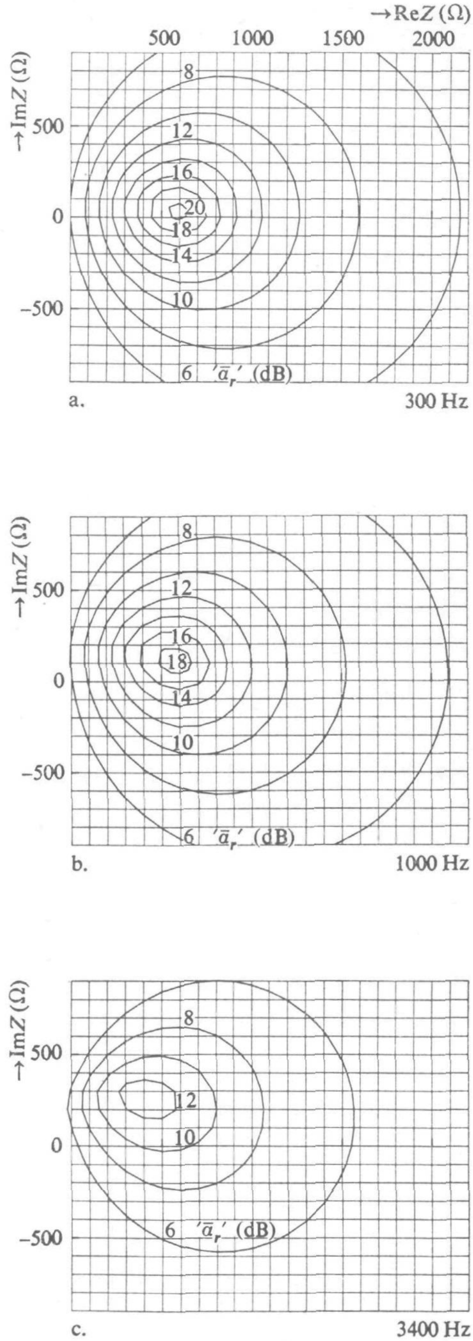
We see again a good agreement between both series of results. Therefore, in our further study we shall consider the results of the model network sufficiently representative of the national network and take only these results into consideration.

The results in Table 5.3 compared with those of Table 5.2 show that an important improvement in return loss can be obtained if it is possible to realize the optimum standard terminating impedance with sufficient accuracy.



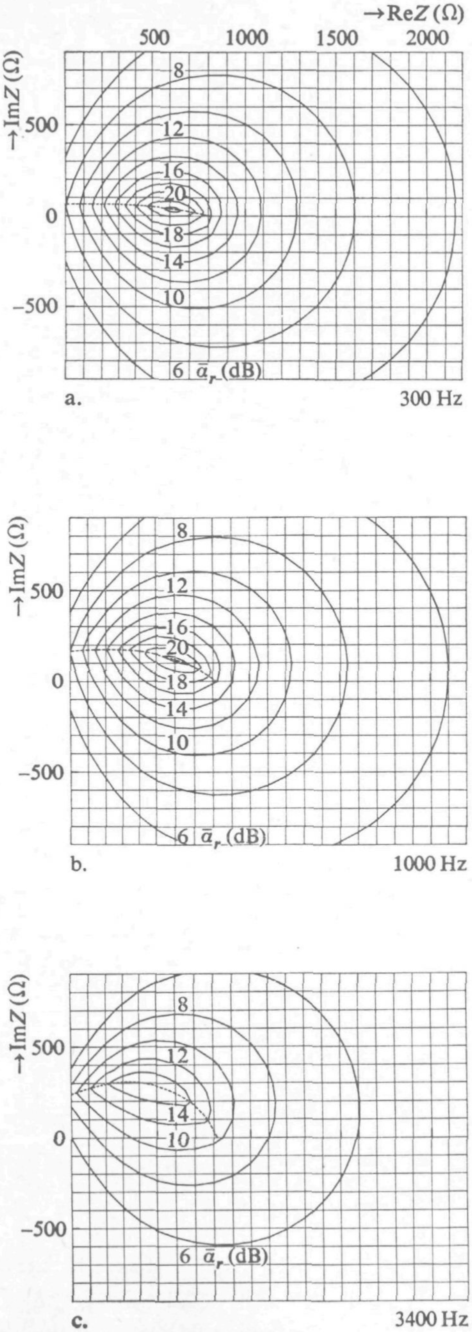
Survey

Figure 5.4



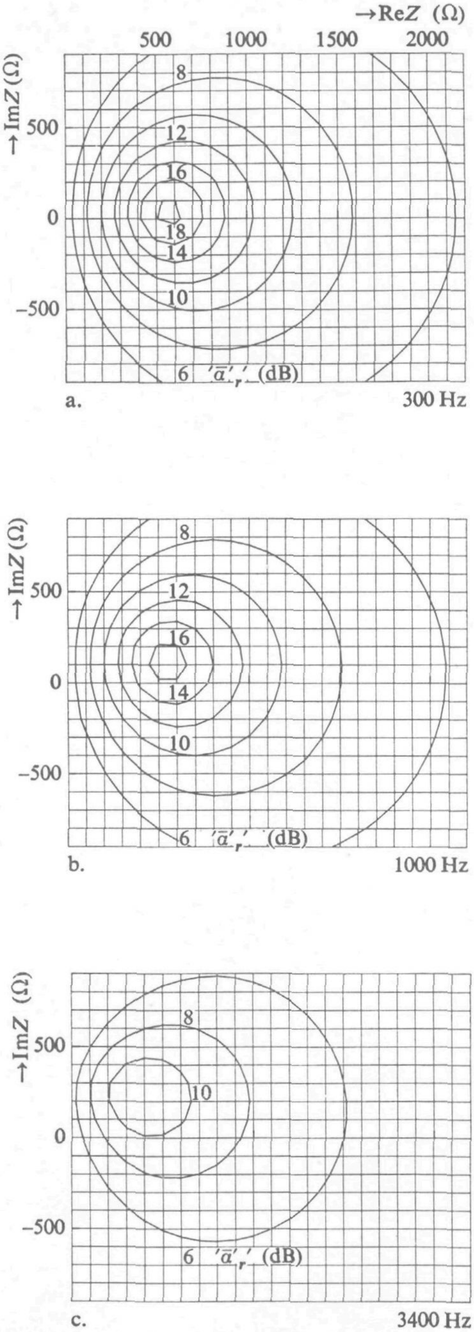
Model network

Figure 5.5



'Mean return loss'

Figure 5.6



'Mean power'

Figure 5.7

Table 5.3

Frequency	Survey Z_{opt}	'$\bar{\alpha}_r$'	Model network Z_{opt}	'$\bar{\alpha}_r$'
300 Hz	620 + j 40 Ω	20.1 dB	591 + j 40 Ω	20.6 dB
500	610 + j 70	19.8	586 + j 67	20.2
1000	590 + j 130	18.3	566 + j 129	18.8
1500	550 + j 180	16.8	535 + j 181	17.2
2000	520 + j 215	15.4	500 + j 219	15.8
2500	480 + j 250	14.1	471 + j 245	14.6
3000	440 + j 270	13.2	441 + j 266	13.5
3400	410 + j 275	12.5	416 + j 278	12.8
echo		16.5		17.0

At this stage, it is appropriate to come back to the influence on the results, caused by the manner of weighting discussed in the preceding paragraph. Similar curves as presented in Figures 5.5a, b and c were determined for weighting based on return loss (Figures 5.6a, b and c) and on the power of reflected signals (Figures 5.7a, b and c). Compared with Figures 5.5a, b and c there are only significant differences in shape and position of the curves that are close to the optimum; especially for the results of weighting based on return loss we note a less regular shape of the curves. This is caused by the influence of some very high values of return loss, an effect which was mentioned in Paragraph 5.4.1; it makes this method basically unsuitable for our purpose. The impedances giving rise to such high values are shown in Figure 5.2; they have further been indicated (dotted line) in Figures 5.6a, b and c, where their influence is clearly visible.

Using the different types of weighting, we determined the impedances resulting in the maximum value of 'weighted return loss'. The results are given in Table 5.4.

Table 5.4

Freq.	Optimum impedance, reflections weighted by *a* Mean amplitude	*b* Mean power	*c* Mean return loss	Return loss of *b* against *a*	*c* against *a*
300 Hz	591 + j 40 Ω	569 + j 37 Ω	625 + j 37 Ω	34.4 dB	31.1 dB
1000	566 + j 129	541 + j 116	609 + j 118	32.1	28.6
3400	416 + j 278	382 + j 235	453 + j 299	24.8	27.8

The mutual differences in this table are relatively small; expressed as return loss against the impedance found with the method we adopted (column *a*) the differences correspond to values (last columns of Table 5.4) that are high compared with usual tolerances for terminating impedances (see Paragraph 5.5.4).

5.5 *Approximation and realization of optimum impedance*

5.5.1 *Accurate approximation*

The shape of the optimum impedance found for the model network (Table 5.3) when depicted in the complex impedance plane (see Figure 5.8) shows that this impedance can only be approximated accurately by a network of higher order. According as the frequency increases, there is an increasing positive imaginary part, together with a decreasing real part. This indicates a two-pole of at least second order [17], which results in rather complicated networks, unless a transformer is used. The basic circuit diagram of such a two-pole is given in Figure 5.9. Several equivalent circuits with five elements are possible; they all contain at least one transformer [18].

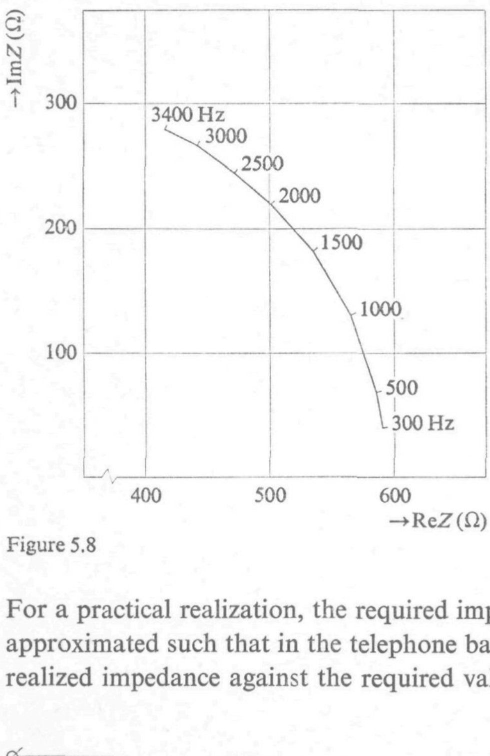


Figure 5.8

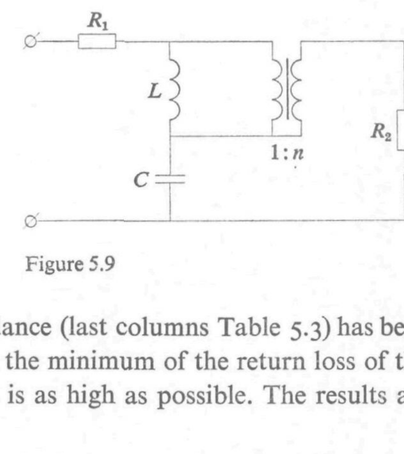


Figure 5.9

For a practical realization, the required impedance (last columns Table 5.3) has been approximated such that in the telephone band the minimum of the return loss of the realized impedance against the required value is as high as possible. The results are

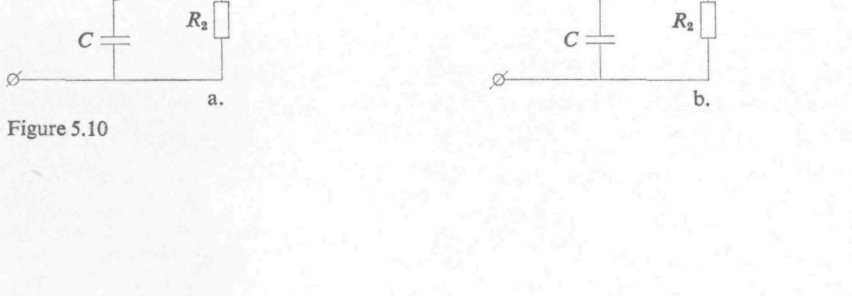


Figure 5.10

Table 5.5

Freq.	Required impedance		First approximation, Figure 5.10a			Second approximation, Figure 5.10b		
	Z	'$\bar{\alpha}_r$'	Z	'$\bar{\alpha}_r$'	Return loss d-b	Z	'$\bar{\alpha}_r$'	Return loss g-b
300 Hz	591 + j 40 Ω	20.6 dB	547.7 + j 25.2 Ω	20.3 dB	27.9 dB	598.6 + j 23.7 Ω	20.5 dB	36.4 dB
500	586 + j 67	20.2	546.1 + j 42.1	19.8	27.7	596.1 + j 39.7	20.0	32.2
1000	566 + j 129	18.8	538.7 + j 84.9	18.3	26.7	584.6 + j 80.6	18.4	27.1
1500	535 + j 181	17.2	526.6 + j 129.1	16.9	26.5	565.6 + j 124.2	16.9	25.0
2000	500 + j 219	15.8	509.7 + j 175.4	15.6	27.7	539.5 + j 171.5	15.6	25.1
2500	471 + j 245	14.6	488.3 + j 224.4	14.5	32.0	506.8 + j 223.8	14.5	28.3
3000	441 + j 266	13.5	462.6 + j 276.9	13.5	32.8	468.1 + j 282.4	13.5	30.5
3400	416 + j 278	12.8	439.2 + j 321.9	12.6	26.5	433.5 + j 334.6	12.5	25.0
echo		17.0		16.7			16.7	
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*

shown in columns *d*, *e* and *f* of Table 5.5; the corresponding network is given in Figure 5.10a.

This circuit diagram contains some simplifications compared with Figure 5.9, because in the optimum approximation the value of R_1 in Figure 5.9 should be zero, and because the transformer and the inductance have been combined in one tapped coil.

An interesting point is that the circuit of Figure 5.10a contains only one resistor (R_2) and that the part of the network between the line terminals and this resistor R_2 is in principle loss-free. Moreover, the value of R_2 is close to 600 Ω. We could, therefore, choose $R_2 = 600\ \Omega$ (the international standard value) and consider this resistance as the termination and the rest of the circuit as an additional loss-free correction network. The results are given in the columns *g*, *h* and *i* of Table 5.5 and in Figure 5.10b. The other components were chosen in order to obtain the highest value for the minimum in column i. Although this second approximation is somewhat less accurate, a minimum return loss of 25 dB against the optimum impedance still seems very reasonable, in view of practical tolerances.

The values of 'weighted return loss' in Table 5.5 for both approximations are close to the optimum (column *c*); mutual differences are very small. Averaged over the frequency band (echo) the difference in 'weighted return loss' between both approximations is negligible.

The networks given in Figure 5.10 generally have the disadvantage that they contain a transformer (or tapped coil) which is an inconvenient complication in the circuit design and will usually increase costs. Of course, equivalent networks not containing a transformer can be realized. However, they will have a considerably greater number of components and generally more than one resistance, which means that equipment with a real impedance cannot be incorporated in the correction network without causing loss. Therefore it seems useful to consider other approximations of the optimum impedance.

5.5.2 *Resistance combined with series-inductance*

A simpler approximation of the required impedance (see Figure 5.8) can be obtained by a resistance in series with an inductance. In that case the real part of the impedance is constant, whereas the optimum value of the frequency-dependent imaginary part can still be chosen. For several values of the real part and for a range of frequencies, the value of the imaginary part corresponding to the maximum obtainable value of 'weighted return loss' was calculated. The results are given in Figure 5.11. These curves

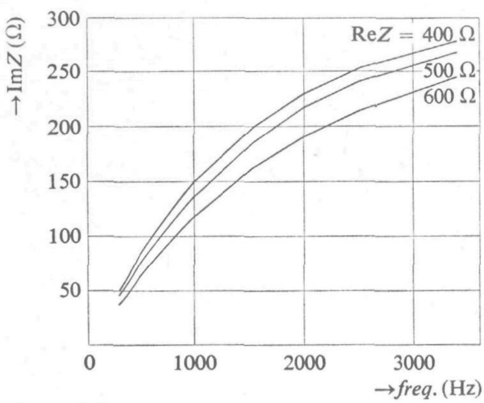


Figure 5.11

show that the imaginary part cannot be realized in one network for all frequencies, because of the decreasing slope at higher frequencies [19]. The best approximation is a series-inductance, which offers an imaginary part linearly increasing with the frequency. In that case the network consists of a resistance (R) in series with a coil (L). The choice of the values of these components depends on the importance attached to the resulting 'weighted return loss' at different frequencies; the optimum imaginary part can only be obtained at one frequency in the telephone band. We based our choice on the consideration that for reasons of stability it is important that the minimum of 'weighted return loss' in the band should be as high as possible. Therefore, in each combination of R and L that value of L was chosen giving the optimum result at 3400 Hz.* The result of this approach with several values of the real part is given in Table 5.6. This table shows an optimum around a real value of 600 Ω at lower frequencies; at higher frequencies the optimum is found at lower resistance values, but the optimum is not very distinct. Also the values obtained for echo show a flat optimum

* It is also possible to choose the value of L such that 'weighted echo return loss' (see Par. 5.4.1) is as high as possible. In that case '$\bar{\alpha}$' at frequencies around about 1500 to 2000 Hz will be higher and close to the optimum; at 3400 Hz values will be somewhat lower. The resulting effect on 'weighted echo return loss' will be an increase of only a few tenths of a dB.

Table 5.6

Values of '$\bar{\alpha}_r$' with several terminating impedances

Z (Ω):	400 + jωL	500 + jωL	550 + jωL	600 + jωL	700 + jωL
L:	13.1 mH	12.6 mH	11.9 mH	11.6 mH	9.9 mH
300 Hz	17.0 dB	19.5 dB	20.3 dB	20.5 dB	19.3 dB
500	16.8	19.1	19.8	20.0	18.8
1000	16.1	17.9	18.3	18.3	17.2
1500	15.5	16.6	16.8	16.6	15.6
2000	14.8	15.5	15.4	15.2	14.1
2500	14.1	14.4	14.2	13.9	12.9
3000	13.4	13.4	13.1	12.8	11.8
3400	12.8	12.6	12.3	11.9	11.0
echo	15.2	16.3	16.4	16.3	15.3

at a real value close to 600 Ω. Therefore, we prefer to use this internationally standardized value and to consider the series-inductance as a separate correction network associated with the line and not forming part of the equipment connected to the line. Then the inductance should be installed separately at the subscribers' premises, which is an unattractive solution from an operational point of view.

5.5.3 *Resistive termination*

The next step, of course, is to consider a solution with a purely resistive terminating impedance. The resulting values for 'weighted return loss' with a series of resistances are listed in Table 5.7.

Table 5.7

Values of '$\bar{\alpha}_r$' with several terminating impedances

Z:	400 Ω	500 Ω	550 Ω	600 Ω	700 Ω	800 Ω
300 Hz	16.7 dB	19.1 dB	19.9 dB	20.1 dB	19.1 dB	16.7 dB
500	16.2	18.4	19.0	19.3	18.4	16.3
1000	14.9	16.4	16.8	16.9	16.3	14.8
1500	13.6	14.6	14.8	14.8	14.3	13.3
2000	12.4	13.1	13.2	13.2	12.8	11.9
2500	11.5	11.9	12.0	11.9	11.5	10.8
3000	10.7	10.9	10.9	10.8	10.5	9.9
3400	10.1	10.3	10.3	10.2	9.8	9.3
echo	13.4	14.3	14.5	14.5	14.1	13.1

In this table we see that in an important part of the frequency band the values close to 600 Ω offer the best results. At the highest frequencies the optimum is at somewhat lower resistance values, but the optimum is again very flat. At all frequencies the results with 600 Ω are significantly better than those with the present nominal impedance of 800 Ω, and also much better than those obtained with the present telephone set Table 5.2). Nevertheless, the values of 'weighted return loss' which are realized are lower than those obtainable with an accurate approximation of the optimum impedance (Table 5.5).

Here it should be noted that, due to tolerances, terminating impedances will always show deviations from their nominal value. This means that the results calculated above will only partly be obtained in practice. This is the reason why we shall consider the influence of these deviations.

5.5.4 *Influence of tolerances of terminating impedances*

An estimate of a reasonable tolerance for terminating impedances can be obtained by means of a comparison with relevant requirements for other equipment in the two-wire part of the telephone network. Here we would refer to the specification for local exchanges, mentioned in Section 5.1, which states return losses of at least 10 dB ($<$ 600 Hz) and 14 dB ($>$ 600 Hz). Some guidance can also be found in the tolerance given in the CEPT-Specification for the multi-frequency sender in telephone sets for push button dialing. A minimum return loss of 14 dB against the nominal impedance has been specified [20]. With a view to these values it seems reasonable to consider the effect of deviations corresponding to a return loss of 14 dB. This value is sufficiently realistic for a telephone set with a stable microphone; with a carbon microphone even larger deviations can be expected.

In Paragraphs 5.5.2 and 5.5.3 we already noted that optima were not pronounced, which means that small impedance deviations will have a minor effect on 'weighted return loss'. However, a tolerance limit corresponding to a return loss of 14 dB allows of considerable deviations; for example, for a nominal value of 600 Ω the real part of the impedance may vary between 400 and 900 Ω. The tolerance area in the complex impedance plane can be represented by a circle, with the centre somewhat beside the nominal value [16].

So, in practice, we can expect values of terminating impedances located in a circular area, which, if inserted in Figures 5.5a, b and c shows the effect on 'weighted return loss'. For the values of terminating impedances involved in this study this circle has a diameter of about 500 Ω. Consequently, the results in the tolerance area may vary considerably. To obtain some insight into this effect, at three frequencies and for several terminating conditions, the minimum and the maximum value of the 'weighted return loss' for impedances in a tolerance area corresponding to a return loss of 14 dB or higher, were calculated.

Together with the value of 'weighted return loss' corresponding to the nominal value of the terminating impedance, the results are listed in Table 5.8. From this table we see

Table 5.8

Values of '$\bar{\alpha}_r$' in a tolerance area corresponding to a return loss of 14 dB

Z:	Optimum impedance		600 Ω + 11.6 mH	600 Ω	800 Ω	Telephone set
	Nominal	20.6 dB	20.5 dB	20.1 dB	16.7 dB	12.6 dB
300 Hz	Maximum	20.6	20.6	20.6	20.6	16.8
	Minimum	14.5	14.4	13.9	10.6	9.5
	Nominal	18.8	18.3	16.9	14.8	13.4
1000 Hz	Maximum	18.8	18.8	18.8	18.6	18.3
	Minimum	13.5	13.2	12.0	9.9	8.6
	Nominal	12.8	11.9	10.2	9.3	7.1
3400 Hz	Maximum	12.8	12.8	12.3	11.8	9.9
	Minimum	9.8	8.8	7.9	7.0	5.1

that the effect of deviations in the terminating impedance on the values of 'weighted return loss' is fairly limited, as could be expected, owing to the attenuation of the line. Considering the total range of values of 'weighted return loss' corresponding to the tolerance range at each frequency, we should bear in mind that generally impedances at the border of the tolerance area will be rare. The designer will save as much room as possible for random variations in component values, and consequently systematic deviations will be kept small in the design with nominal values. However, if considerable deviations are allowed (and this is the case with a return loss of 14 dB), it may for economic reasons be attractive to use at least part of the available room systematically, e.g. at lower frequencies by choosing a smaller transformer or capacitor. So it is reasonable to assume that in the tolerance area the nominal value is the main point; but in a decreasing likelihood towards the boundaries, all other values in this area may occur in practice.

Table 5.8 shows that with respect to the resulting values of 'weighted return loss', tolerances do not change the mutual order of the different terminations.

5.6 *Additional measures in the local exchange*

5.6.1 *Series-inductance*

If for practical reasons a resistive impedance is preferred as standard termination in the telephone network (in that case the internationally standardized value of 600 Ω is very appropriate in the Dutch network), it is worth remembering that better results could be obtained by the insertion of a series-inductance (see Paragraph 5.5.2). We already indicated the possibility of considering this inductance as a separate correction network associated with the line. Now it is interesting to consider the insertion of a correction network at the input of the subscriber's line in the local exchange. It is to be expected that a series-inductance will also have a favourable effect in this case. Here a compensation of the capacitive component of the input-impedance of the line seems possible too, and would probably be even more effective than at the subscriber's end, because now the effect is not reduced by the attenuation of the cable.

First of all we shall consider the effect of a purely inductive series-impedance at the input of the line. Such an impedance in itself causes no loss (no dissipation), but it influences matching conditions and this will have some effect on the insertion loss (see Section 5.7).

We can calculate the optimum value of series-inductance at several frequencies. The results, together with the corresponding values of 'weighted return loss' are given in the first columns of Table 5.9.

Table 5.9

Frequency	Optimum series-inductance		$L_s = 14.0$ mH	
	Z_s	'$\bar{\alpha}_r$'	Z_s	'$\bar{\alpha}_r$'
300 Hz	+j 44 Ω	20.9 dB	+j 26 Ω	20.7 dB
500	+j 73	20.8	+j 44	20.4
1000	+j 166	20.6	+j 88	19.4
1500	+j 253	19.4	+j 132	18.0
2000	+j 280	17.3	+j 176	16.6
2500	+j 292	15.5	+j 221	15.2
3000	+j 298	13.9	+j 265	13.8
3400	+j 300	12.8	+j 300	12.8
echo		18.4		17.6

These results look very promising; however, the shape of the optimum inductance as a function of frequency is similar to the curves in Figure 5.11. This means that the most suitable approximation is a simple inductance. Once more, the value of the inductance has been chosen such that the minimum value of the 'weighted return loss' in the telephone band is as high as possible (optimum value at 3400 Hz). So we obtain the results given in the second part of Table 5.9. We conclude that with this simple correction network (only series-inductance) very good results can still be obtained, even better than those obtainable with the theoretical optimum standard termination at the subscriber's end of the line (see Table 5.3).

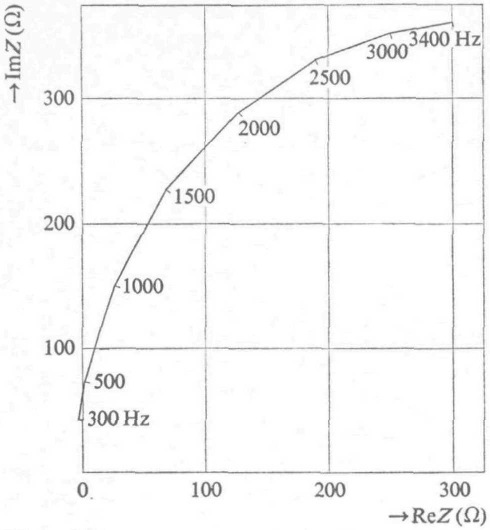


Figure 5.12

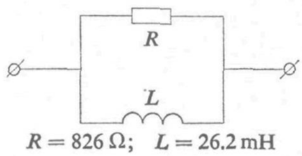


Figure 5.13

5.6.3 *Quadripole correction network*

A drawback of the complex series-impedance described in Paragraph 5.6.2 is the additional transmission loss it causes (see Section 5.7). The very good results at higher frequencies, compared with those of a single inductance, emanate from the additional correction of the–on an average–too small a real part of the input-impedance of the subscribers' lines. We would prefer to effect such a correction by means of non-dissipative elements. This could be realized by placing an inductive impedance parallel with the line, which compensates the capacitive part of the input-impedance and transforms the real part of this impedance. A closer examination will soon show that an inductance is needed of which the value decreases at an increasing frequency. Such an impedance, however, is physically impossible.

This problem can be solved by adding–in series with the line–an inductance with a value higher than needed for compensation of the capacitive part of the input-impedance of the line, and placing a capacitor parallel with this combination in order to

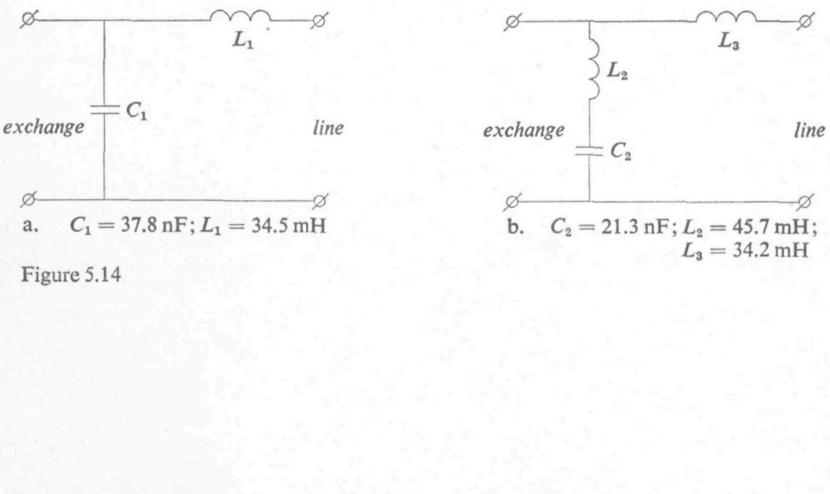


Figure 5.14

correct the imaginary part and to transform the real part of the impedance. The diagram of such a network is given in Figure 5.14a. The values of the components were determined such that the highest possible value of the minimum 'weighted return loss' is obtained at the frequencies in Table 5.11. The resulting values of 'weighted return loss' are shown in the first part of this table. These results indicate an improvement

Table 5.11

Freq.	$C_1 = 37.8\,\mathrm{nF}; L_1 = 34.5\,\mathrm{mH}$ '$\bar{\alpha}_r$'	$C_2 = 21.3\,\mathrm{nF}; L_2 = 45.7\,\mathrm{mH}; L_3 = 34.2\,\mathrm{mH}$ '$\bar{\alpha}_r$'
300 Hz	20.5 dB	20.8 dB
500	20.0	20.7
1000	18.8	20.2
1500	18.1	19.4
2000	17.9	18.5
2500	17.9	17.9
3000	18.1	17.9
3400	17.9	17.9
echo	18.3	19.2

compared with those in the right-hand part of Table 5.9. A closer examination shows that at 3400 Hz the result is very close to the maximum obtainable with such a network; but at the frequencies in the middle of the band better results could be obtained with higher values of the parallel impedance. Such values can be effected (while retaining the favourable results at higher frequencies) if we replace the capacitor by a series-resonant circuit (see Figure 5.14b). Values of components could be chosen such that the minimum value of 'weighted return loss' is as high as possible, while at the same time the value weighted for echo can be optimized. The results are given in the second part of Table 5.11. They again show a (relatively small) improvement.

5.6.4 *Optimum balance impedance*

As mentioned in Section 5.1, in some conditions (local exchange and primary centre in the same building; four-wire circuit up to the local exchange) the loaded cable between subscriber's line and terminating set will not be available. For these situations it is interesting to determine the optimum values of the impedance of the balancing network at the four-wire terminating set, with subscribers' lines terminated in 600 Ω. A first estimate of the values to be expected can be found by subtracting the values found in Table 5.10 from 820 Ω. A direct determination of the optimum (i.e. the value corresponding to the highest possible value of 'weighted return loss') results in (slightly) different values, owing to the fact that now in the formula for the reflection coefficient the value of the reference impedance is varying. In Table 5.12 the results for three frequencies are listed. The results for 'weighted return loss' are very good, even compared with those in Table 5.10 obtained with the optimum series-impedance, taking into account that in the present case no additional transmission loss has been introduced.

Table 5.12

Frequency	820–Z_s	Optimum balance impedance	
		Z	'$\bar{\alpha}_r$'
300 Hz	823 – j 43 Ω	858 – j 52 Ω	21.1 dB
1000	793 – j 152	821 – j 167	20.9
3400	522 – j 360	565 – j 352	19.3

5.7 *Other effects of impedance correction*

A change of nominal terminating impedance and introduction of impedance correcting networks will influence insertion loss. In this respect we shall consider correcting networks to form part of the cable. Networks without resistance, either inserted at the beginning of the line or at the end, will not introduce loss, but change (and on an average improve) matching conditions, and therefore affect the insertion loss.

For the more complex series-impedance of Paragraph 5.6.2 the situation is different. Here additional loss will occur, and we can hardly expect that this will be compensated by improved matching conditions.

In Table 5.13 the insertion loss calculated for several conditions is given for 0.5 mm cable, together with the values of RE calculated in accordance with Section 3.2.

Since correction networks are considered as forming part of the line, there is already some insertion loss in some cases, even for zero line length. From Table 5.13 we can conclude that a change from 800 Ω to 600 Ω, whether or not with additional correction, leads to a small increase in insertion loss at the lower frequencies. With a purely resistive 600 Ω termination there is some decrease in insertion loss, compared with 800 Ω, at higher frequencies, apparently as a result of better matching conditions; for the RE this results in a slight increase only. Compared with the results for the present telephone set (column *b*) the results with 600 Ω (column *c*) show a somewhat larger increase, as already discussed in Paragraph 4.2.1.

In Table 5.13 the effect of better impedance matching obtained by the various impedance correcting network (columns *d* to *i*) is clearly noticeable in the insertion loss at higher frequencies (compare column *c*). But this effect weighted for loudness (RE) is very limited. Column *g* shows the additional loss caused by the dissipative component in the correction network.

Table 5.13

Send/rec. impedance	*a.* 800 Ω/800 Ω				*b.* 800 Ω/telephone set			
Length:	0 km	1.5 km	3 km	5 km	0 km	1.5 km	3 km	5 km
300 Hz	0 dB	1.3 dB	2.5 dB	3.9 dB	0 dB	1.8 dB	3.2 dB	4.8 dB
500	0	1.3	2.5	4.1	0	1.6	3.0	4.5
1000	0	1.4	2.8	4.8	0	1.2	2.4	4.0
2000	0	1.6	3.7	6.9	0	0.9	2.5	5.7
3400	0	2.1	5.3	9.9	0	1.7	5.2	10.1
RE	0	1.5	3.1	5.4	0	1.2	2.7	4.9

Send/rec. impedance	*c.* 800 Ω/600 Ω				*d.* 800 Ω/$j\omega L_1 + 600$ Ω			
Length:	0 km	1.5 km	3 km	5 km	0 km	1.5km	3 km	5 km
300 Hz	0 dB	1.5 dB	2.8 dB	4.3 dB	0.00 dB	1.5 dB	2.8 dB	4.3 dB
500	0	1.5	2.8	4.4	0.00	1.5	2.8	4.4
1000	0	1.5	3.0	5.0	0.01	1.5	2.9	4.9
2000	0	1.7	3.7	6.8	0.05	1.5	3.4	6.4
3400	0	2.1	5.1	9.5	0.13	1.6	4.5	9.0
RE	0	1.6	3.3	5.6	0.03	1.5	3.1	5.4

Send/rec. impedance	*e.* 800 Ω/$L_2, C_2, n + 600$ Ω				*f.* $800 + j\omega L_3$Ω/600 Ω			
Length:	0 km	1.5 km	3 km	5 km	0 km	1.5 km	3 km	5 km
300 Hz	0.00 dB	1.5 dB	2.8 dB	4.3 dB	0.00 dB	1.5 dB	2.8 dB	4.3 dB
500	0.01	1.5	2.8	4.4	0.00	1.5	2.8	4.4
1000	0.03	1.5	2.9	4.9	0.02	1.5	2.9	4.9
2000	0.15	1.6	3.4	6.4	0.07	1.6	3.5	6.5
3400	0.62	1.6	4.1	8.7	0.19	1.8	4.7	9.1
RE	0.08	1.5	3.1	5.3	0.04	1.5	3.1	5.5

Send/rec. impedance	*g.* $800 + R, L_4/600\ \Omega$				*h.* $800 + C_5, L_5/600\ \Omega$			
Length	0 km	1.5 km	3 km	5 km	0 km	1.5 km	3 km	5 km
300 Hz	0.02 dB	1.5 dB	2.8 dB	4.3 dB	0.00 dB	1.5 dB	2.8 dB	4.3 dB
500	0.06	1.5	2.8	4.4	0.00	1.5	2.8	4.4
1000	0.25	1.7	3.0	4.9	-0.01	1.5	3.0	4.9
2000	0.83	2.2	4.0	7.1	0.01	1.6	3.4	6.4
3400	1.71	3.3	6.3	10.9	0.34	1.7	4.2	8.6
RE	0.44	1.9	3.4	5.7	0.01	1.5	3.1	5.4

Send/rec. impedance	*i.* $800 + L_6, C_6, L_7/600\ \Omega$				*j.* Charact. imp./charact. imp.			
Length:	0 km	1.5 km	3 km	5 km	0 km	1.5 km	3 km	5 km
300 Hz	0.00 dB	1.5 dB	2.8 dB	4.3 dB	0 dB	1.0 dB	2.0 dB	3.3 dB
500	0.01	1.5	2.8	4.4	0	1.3	2.5	4.2
1000	0.03	1.5	2.9	4.8	0	1.8	3.6	5.9
2000	0.10	1.6	3.4	6.4	0	2.5	5.0	8.3
3400	0.32	1.7	4.2	8.6	0	3.0	6.4	10.6
RE	0.06	1.5	3.1	5.3	0	1.9	3.8	6.4

d. $L_1 = 11.6$ mH (Paragraph 5.5.2)
e. $L_2 = 44.34$ mH, $C_2 = 23.75$ nF, $n = 0.31$ (Paragraph 5.5.1)
f. $L_3 = 14.0$ mH (Paragraph 5.6.1)
g. $R = 826\ \Omega$, $L_4 = 26.2$ mH (Paragraph 5.6.2)
h. $L_5 = 34.5$ mH, $C_5 = 37.8$ nF (Paragraph 5.6.3)
i. $L_6 = 45.7$ mH, $C_6 = 21.3$ nF, $L_7 = 34.2$ mH (Paragraph 5.6.3)

To some extent all the impedance correcting networks show the properties of a low-pass filter. Therefore, they will introduce additional insertion loss, generally at frequencies considerably higher than those in the telephone band. In this respect the networks of columns *e* (Paragraph 5.5.1) and *i* (Paragraph 5.6.3) have a specific effect; these networks contain a shunt-impedance with a series-resonant circuit and this will cause a peak in insertion loss at 8.8 kHz and 5.1 kHz respectively. As far as telephony is concerned this is not important.

Another effect of the insertion of impedance correcting networks in subscribers' lines, as discussed in the preceding sections, is that the impedance which the line presents to the telephone set will change, as compared with the present situation. This is important with regard to sidetone conditions; a correction of the balance impedance within the telephone set may be required, especially for the higher frequencies where the impedance corrections show the greatest effect. We can expect that, due to the attenuation of the line, the influence on sidetone, on an average, will be less for correction networks at the exchange end of the line than for those at the subscriber's end.

5.8 *Critical consideration*

So far, we have only considered impedance conditions in terms of 'weighted return loss'. Now it seems useful to pay attention to the distribution of return losses consequent on the various situations we studied in the preceding sections. In Figures 5.15a, b and c the cumulative distribution curves of return loss against 820 Ω at three signal

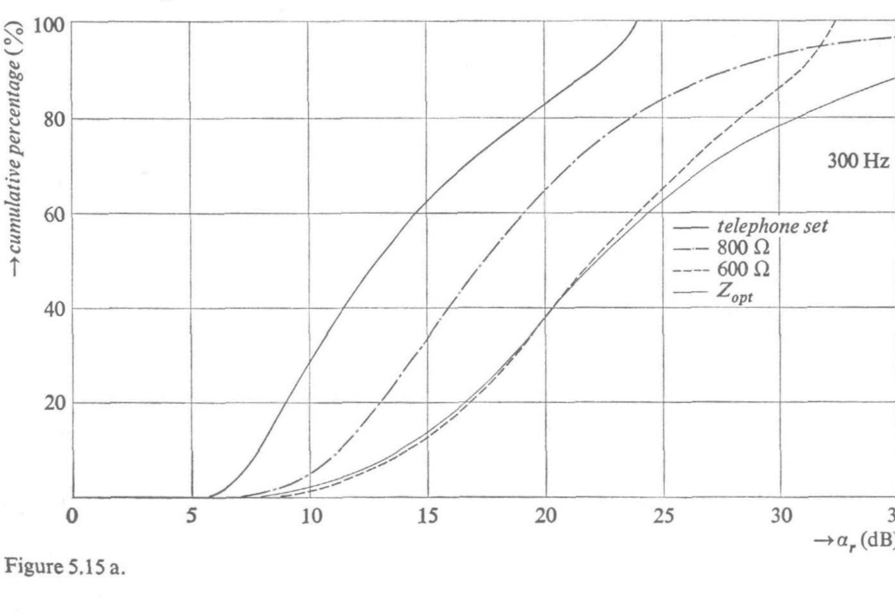


Figure 5.15 a.

5.6.2 *Complex series-impedance*

Seeing the good results obtained in the preceding paragraph the question may be put whether it is possible to apply a more complicated network at the input of the lines, in order to obtain even better results. For this purpose we determined the value of the (complex) series-impedance, giving maximum values of 'weighted return loss', for subscribers' lines terminated in 600 Ω. The results are given in the first part of Table 5.10.

Table 5.10

Frequency	Optimum series-impedance		Approximation	
	Z_s	'$\bar{\alpha}_r$'	Z_s	'$\bar{\alpha}_r$'
300 Hz	-3 + j 43 Ω	20.9 dB	3 + j 49 Ω	20.8 dB
500	2 + j 73	20.8	8 + j 88	20.8
1000	27 + j 152	20.7	32 + j 159	20.7
1500	68 + j 227	20.7	68 + j 227	20.7
2000	126 + j 288	20.8	114 + j 284	20.8
2500	190 + j 330	21.0	165 + j 330	20.9
3000	252 + j 352	21.3	218 + j 364	21.0
3400	298 + j 360	21.5	261 + j 384	21.1
echo		20.7		20.7

These results are extremely good indeed. The 'weighted return loss' is nearly constant all over the frequency band at a value of about 21 dB. The improvement at higher frequencies is very considerable. However, it is also clear that this series-impedance will introduce additional transmission loss.

Now it is important whether this optimum series-impedance can be realized by a simple network with sufficient accuracy. The optimum series-impedance is plotted in the complex impedance plane in Figure 5.12. This curve reminds us of the one of a resistance parallel to an inductance. For a realization of such a circuit we chose the values of components such that the lowest values of 'weighted return loss' (around 1500 Hz) are as high as possible. The results are shown in the right-hand part of table 5.10; they approach the optimum results very closely. The corresponding network is given in Figure 5.13.

The composition of this network equals the one mentioned in Section 5.2, which was studied in North-America to be introduced at a similar point in the connection [8]. But the values of the components, especially the resistance, differ considerably, possibly as a result of other electrical and statistical conditions, and of the method used to determine the values.

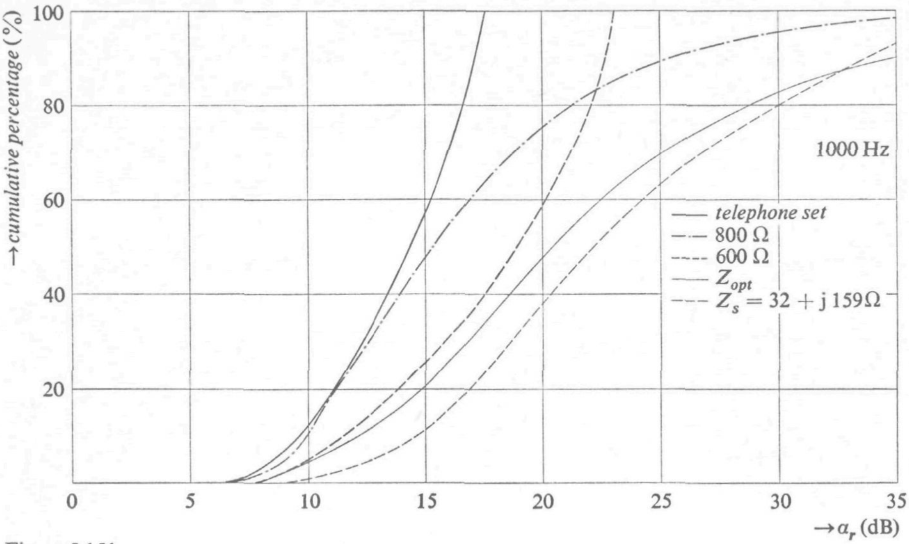


Figure 5.15 b.

frequencies are drawn for several conditions. At the lower frequencies (Figure 5.15a) mutual differences between the various situations with a terminating impedance of 600 Ω, whether or not with additional correction, are small. Therefore, only two examples of this category have been plotted. At the highest frequency (Figure 5.15c)

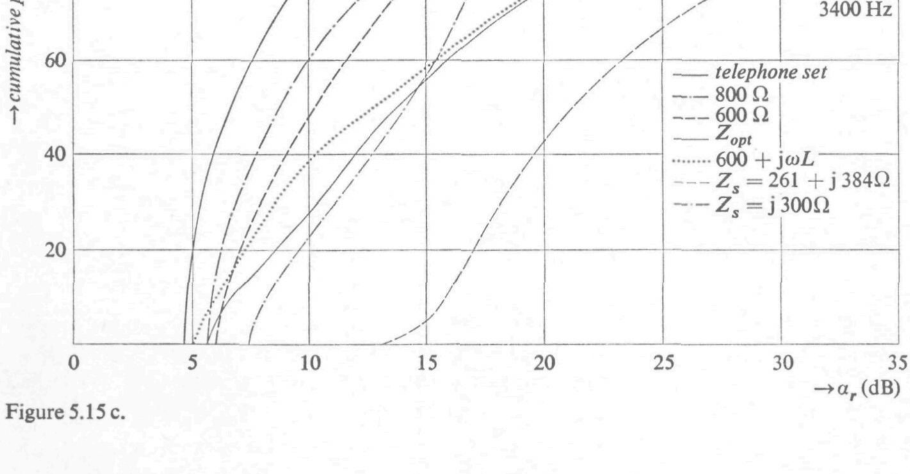


Figure 5.15 c.

differences are more pronounced. The curves in Figures 5.15a, b and c show the effect of our method of weighting (Paragraph 5.4.1) and the emphasis which it places on lower values of return loss. We also see the favourable effect on the distribution which will result from a change of the present nominal terminating impedance of 800 Ω and the impedance of the present telephone set, to a standard terminating impedance of 600 Ω.

In order to facilitate a comparison, the resulting values of 'weighted return loss' for the various conditions discussed in the preceding sections and presented there in separate tables, have been summarized in Table 5.14. The sequence of the columns is the same as that of Table 5.13.

Table 5.14

Values of '$\bar{\alpha}_r$' in dB

	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*
Subscr. end:	800 Ω	Tel. set	600 Ω	600 Ω $+L_1$	600 Ω + L_2, C_2, n	600 Ω	600 Ω	600 Ω	600 Ω	Char. Z
Exch. end:	—	—	—	—	—	L_3	R/L_4	C_5, L_5	$L_6C_6L_7$	—
Table no:	5.7	5.2	5.7	5.6	5.5	5.9	5.10	5.11	5.11	5.1
300 Hz	16.7	12.6	20.1	20.5	20.5	20.7	20.8	20.5	20.8	5.6
1000 Hz	14.8	13.4	16.9	18.3	18.4	19.4	20.7	18.8	20.2	7.8
3400 Hz	9.3	7.1	10.2	11.9	12.5	12.8	21.1	17.9	17.9	6.7
echo	13.1	11.6	14.5	16.3	16.7	17.6	20.7	18.3	19.2	7.5

From this table it is clear that termination of subscribers' lines in their characteristic impedance yields poor results. The present nominal impedance of 800 Ω and the impedance of the present telephone set, too, show results that are far from being optimum. A changeover to a terminating impedance of 600 Ω, the international standard value, as a first step,* already produces a significant improvement. Additional correction networks result in further improvements. In this respect the table shows that corrections inserted at the exchange end offer better results than those obtained with correction at the subscriber's end. Moreover, installation in the local exchange offers practical advantages, e.g. the possibility to use the networks more efficiently by inserting them after the first reduction stage in the exchange (see Paragraph 4.2.6).

Considering the results listed in Table 5.14, we should realize that values of 'weighted

* Possibilities to change the impedance of the telephone sets are available; a change of the present telephone receiver into an electro-dynamic type will lead to a much more resistive impedance. The introduction of a stable microphone with amplifier would next give a more accurate and stable impedance.

return loss' in the order of 18 dB or more, are relatively high compared with the effect of irregularities which can be expected at other points in the two-wire part of a telephone connection. Therefore, the practical importance of such high values of return loss at the input of the subscriber's line will be very limited, because the influence on balance return loss in the four-wire loop will largely be obscured.

An improvement of return loss at the input of the subscribers' lines will, on an average, cause an improvement of balance return loss in the four-wire loop. Consequently, with constant stability and echo conditions, the loss in the four-wire network could be reduced. If this reduction is equally distributed over both directions of transmission, the transmission loss in the connection can be reduced by half the increase in balance return loss. As explained before the latter increase is smaller than that calculated at the input of the subscribers' lines. So the values in column *g* of Table 5.14 should be reduced by at least twice the increase in loss (see Table 5.13). Moreover, in a real telephone network it will be very difficult to start the introduction of additional loss, with the prospect that–for reasons of stability and echo–this loss can be compensated elsewhere in the network in a later stage only.

The above considerations indicate that the correction containing a series-impedance with resistance (column *g*), although offering very high values of 'weighted return loss', is less suitable for practical application.

The other correction networks show a favourable influence (although of minor importance) on insertion loss (see Table 5.13); only for very short lines there is a very small increase in loss compared with the results corresponding to a termination of 600 Ω (column *c*). But for long lines there is a not to be neglected reduction at higher frequencies. The ultimate effect is a reduction of the spread of insertion loss occurring in the network.

The values of 'weighted return loss' obtainable with non-dissipative networks at the exchange end (columns *h* and *i*) seem amply sufficient. Even these networks will only show their full advantage, if combined with improvement of impedance conditions elsewhere in the two-wire network. The insertion of a simple series-inductance at the exchange end (column *f*), already results in a satisfactory effect on echo; however, at the higher frequencies some further improvement could be desirable.

Concerning a choice between the two quadripole networks in columns *h* and *i* in the Tables 5.13 and 5.14, we would observe that the latter offers slightly better results; the values of 'weighted return loss' are already rather high. On the other hand, this network is more complicated, it contains one inductance more (higher costs). Moreover, this network introduces a sharp peak in attenuation at about 5 kHz, which can be a drawback when the subscriber's line is used for purposes other than telephony. Therefore, for practical applications the simpler network (column *h*) is preferred.

5.9 *Conclusions*

From the foregoing the following conclusions can be drawn:

– The terminating conditions of the subscribers' lines have a significant influence on the overall transmission performance of a telephone network.

– It is possible to determine measures which, if uniformly applied to all subscribers' lines, lead to an interesting improvement of stability and echo conditions, with only a minor influence on transmission loss. Such an improvement could be utilized direct to obtain a better telephone transmission performance, or indirect (at a later stage) to decrease the loss of the four-wire transmission chain and consequently the values of overall reference equivalent.

– As a first step towards better terminating conditions in the Netherlands telephone network, it is recommended that the nominal value of the impedance of the telephone sets and of special equipment connected to subscribers' lines be changed into the internationally standardized value of 600 Ω. An average increase in return loss in the order of several dB's can be expected. The change in the impedance of the telephone sets could be realized by replacement of the present telephone receiver by an electrodynamic one; introduction of a stable microphone (with amplifier) would result in a more accurate and stable impedance of the set.

– It was shown that further improvements are possible by the introduction of additional impedance correcting networks. The networks most suitable for this purpose are those inserted at the exchange end of the subscribers' lines. A simple series-inductance will already produce reasonable results.

– Even better results can be obtained by the use of a more complicated network (quadripole with low-pass character). However, in this case the results concerning the impedance conditions on the subscribers' lines are such that they will only show their additional advantage for the overall performance of the telephone network, if the introduction of this correction network is combined with improvement of impedance conditions elsewhere in the two-wire part of the network (local exchange, primary centre, impedance of loaded cables and balancing network).

References Chapter 5

1 CCITT, *Green Book*, Vol. III-1, Recommendation G. 122, pp. 38-42 (ITU, Geneva, 1973).

2 Ramig, G., *Die Genauigkeit der Näherungsformeln für Fehlerdämpfung und Gabelübergangsdämpfung in Gabelschaltungen*. In: Archiv der Elektrischen Übertragung, 15 no. 5 (1961), pp. 245-252.

3 ITU, *List of definitions of essential telecommunication terms*. Part 1: General terms, telephony, telegraphy, p. 46 (ITU, Geneva, 1961).

4 Sondhi, M. M., *An adaptive echo canceller*. In: The Bell System Technical Journal, 46 no. 3 (1967), pp. 497-511.
5 de Jong, C., *Enkele beschouwingen over de impedantiebasis van het Nederlandse telefoonnet*. In: Het PTT-Bedrijf, XIII no. 2 (1964), pp. 81-88.
6 Galjaard, P. J., *Impedantieverbetering en normalisering in het niet-versterkte Nederlandse telefoonnet*. Dr. Neher Laboratorium Memorandum nr. 359 TL, Aug. 1973.
7 Bast, G. H., *Gedachten over de verdere ontwikkeling van het Nederlandse telefoonnet*. In: Het PTT-Bedrijf, III no. 2 (1950), pp. 55-58.
8 CCITT, Handbook *National telephone networks for the automatic service*, Chap. V, pp. 39-40 (ITU, Geneva, 1964).
9 CCITT, *Ibidem*, Chap. V, pp. 37-39.
10 CCITT, *White Book*, Vol. V, Suppl. 7, p. 47, National network (New Zealand) (ITU, Geneva, 1969).
11 CCITT, *Ibidem*, p. 59, National network (South Africa).
12 CCI, *Comité Consultatif International des Communications Téléphoniques à grande distance, Plenary Session 1928*, p. 44.
13 CCITT, *Green Book*, Vol. III-2, Suppl. 1, pp. 555-556 (ITU, Geneva, 1973).
14 Huis, T., *De stand van zaken betreffende de studie ten behoeve van een nieuw dempingsplan*. In: Data, 73 no. 2 (1972), pp. 23-32.
15 CCITT, *Green Book*, Vol. III-2, Suppl. 2, pp. 556-559 (ITU, Geneva, 1973).
16 Bakker, C., *A method to measure the quality of cable terminating impedances*. In: Het PTT-Bedrijf, IX no. 1 (1959), pp. 17-22.
17 Tellegen, B. D. H., *Theorie der wisselstromen III, Theorie der elektrische netwerken*, p. 122 (Noordhoff, Groningen, 1952).
18 Tellegen, B. D. H., *Ibidem*, p. 194.
19 Tellegen, B. D. H., *Ibidem*, p. 176.
20 CEPT, *Group de Travail TTT, Rapport de la Réunion, Bruxelles, Oct. 1974*, Annex 18, p. 147.

Annex A

Loss of an ideal matching network

A linear two-port with image impedances R and Z would offer the ideal matching conditions described in Section 5.2. In that case R is resistive and Z should be equal to the characteristic impedance of a homogeneous line. We shall determine the minimum insertion loss introduced by such a passive matching network.
A generator with an e.m.f. E* and an internal resistance R (see Figure A.1) supplies maximum available power $P_i = \dfrac{|E|^2}{4R}$ to the network if this network has correctly been terminated in Z.

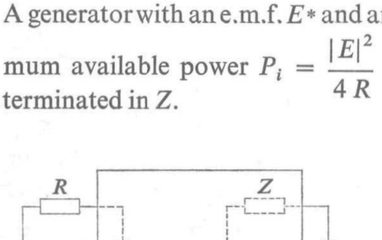


Figure A.1

With this sending conditions, in calculations concerning the output signal, the network can at the right-hand terminals be represented by an e.m.f. E_o with an internal impedance Z. The maximum available power from the network is delivered to the terminating impedance, if this terminating impedance is the conjugate of Z. The power delivered will then be $P_o = \dfrac{|E_o|^2}{4\,\mathrm{Re}Z}$, where ReZ indicates the real part of the complex impedance Z. It is clear that with this termination the input impedance of the network at the left-hand side will deviate from R.
Therefore, we consider the general situation, in which the network is terminated in an impedance Z_o, which differs from the image impedance Z (see Figure A.2a). This situation can be considered as a superposition of the two diagrams in Figure A.2b.

* We apply the well-known complex notation: E stands for (complex) e.m.f. and I for (complex) current. $|E|$ and $|I|$ represent r.m.s. values.

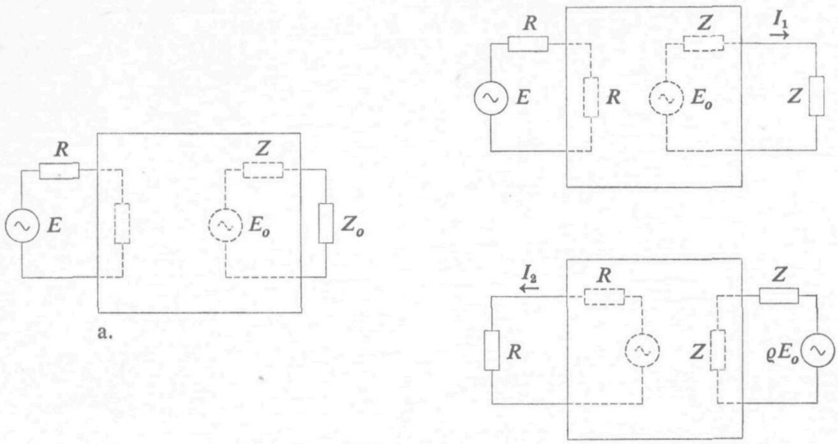


Figure A.2

The top figure under b is identical with Figure A.1. In the lower part ϱ indicates the (voltage) reflection coefficient:

$$\varrho = \frac{Z_o - Z}{Z_o + Z}$$

Taking into account the reciprocity we find $\dfrac{I_2}{\varrho E_o} = \dfrac{I_1}{E}$

Now: $I_1 = \dfrac{E_o}{2Z}$ and, consequently: $I_2 = \varrho \dfrac{E_o^2}{2EZ}$ (A–1)

The power delivered to the network at the left-hand terminals is:

$$P_i = \frac{|E|^2}{4R} - \left|\frac{\varrho E_o^{\,2}}{2EZ}\right|^2 \cdot R = \frac{|E|^2}{4R} - |\varrho|^2 \frac{R}{4} \left|\frac{E_o^{\,2}}{EZ}\right|^2 \qquad \text{(A–2)}$$

This power appears to be equal to the algebraical sum of the powers delivered to the network at the left-hand terminals in the two diagrams of Figure A.2b. This is due to the special circumstance that the internal impedance of the generator and the impedance of the network, seen at the left-hand terminals, are equal and resistive.
If we consider the situation in which Z_o is the conjugate of Z, we find:

$\varrho = \dfrac{Z_o - Z}{Z_o + Z} = -\mathrm{j}\,\dfrac{\mathrm{Im}Z}{\mathrm{Re}Z}$, where ImZ indicates the imaginary part of Z.

The power delivered to the network in this case is:

$$P_i' = \frac{|E|^2}{4R} - \left|\frac{\mathrm{Im}Z}{\mathrm{Re}Z}\right|^2 \frac{R}{4} \left|\frac{E_o^{\,2}}{EZ}\right|^2 \qquad \text{(A–3)}$$

In this condition (Z_o conjugate to Z), the output power of the network is:

$$P_o' = \frac{|E_o|^2}{4\,\mathrm{Re}Z} \tag{A–4}$$

Of course, for a passive network the following holds:

$$P_o' \leqq P_i', \text{ or } \frac{|E_o|^2}{4\,\mathrm{Re}Z} \leqq \frac{|E|^2}{4R} - \left|\frac{\mathrm{Im}Z}{\mathrm{Re}Z}\right|^2 \frac{R}{4} \left|\frac{E_o{}^2}{EZ}\right|^2 \tag{A–5}$$

In the case of subscribers' lines at speech frequencies we have approximately (see formula (5–2)): $\mathrm{Im}Z = -\,\mathrm{Re}Z$ and $|Z| = \sqrt{2}\,\mathrm{Re}Z$.

These values inserted in (A–5) lead to:

$$\frac{|E_o|^2}{4\,\mathrm{Re}Z}\;\frac{4R}{|E|^2} \leqq 1 - \tfrac{1}{2}\left(\frac{|E_o|^2}{4\,\mathrm{Re}Z}\;\frac{4R}{|E|^2}\right)^2 \tag{A–6}$$

The factor $\dfrac{|E_o|^2}{4\,\mathrm{Re}Z}\;\dfrac{4R}{|E|^2}$ represents the ratio of the maximum available power at the output of the network and that of the generator E.

Solving the inequality (A–6) we find:

$$\frac{|E_o|^2}{4\,\mathrm{Re}Z} \leqq (\sqrt{3}-1)\frac{|E|^2}{4R} \tag{A–7}$$

In the normal situation (Figure A.1) the network is terminated in Z. In that case the output power is $P_o = \left|\dfrac{E_o}{2Z}\right|^2 \mathrm{Re}Z$, or for subscribers' lines: $P_o = \dfrac{|E_o|^2}{8\,\mathrm{Re}Z}$; the input power was $P_i = \dfrac{|E|^2}{4R}$. From $(A–7)$ it follows that: $P_o \leqq 0.5\,(\sqrt{3}-1)\,P_i$.

The power loss is at least a factor 0.5 ($\sqrt{3}$ – 1) or expressed in dB: 4.36 dB.

To find the insertion loss of the network we have to consider the situation whereby the line (impedance Z) is connected direct to the generator with resistance R. We assume practical conditions whereby R is 800 Ω and Z is the impedance of 0.5 mm cable. We calculated the mismatch losses occurring in this situation, and also applied weighting for loudness (RE):

300 Hz	1.43 dB
500	1.03
1000	0.80
2000	0.83
3400	1.03
RE	0.88

So the insertion loss of the correction network varies between at least 4.36–1.43 = 2.9 dB and 4.36–0.80 = 3.6 dB. The RE is 4.36–0.88 = 3.5 dB.

Annex B

Glossary

ANTI-SIDETONE CIRCUIT. A circuit inside a telephone set for the purpose of reducing the transmission from the microphone to the associated telephone receiver.
ATTENUATION. 'The progressive diminution in space of certain quantities characteristic of a propagation phenomenon'.*

BALANCE. See: Balancing network.
BALANCE RETURN LOSS. The additional transmission loss introduced between the 'return' and the 'go' path at a four-wire terminating set, which is attributable to balancing conditions. Usually balance return loss is defined as:
'The expression in transmission units of the ratio $\left|\dfrac{W+Z}{W-Z}\right|$, where Z is the value of the impedance at the two-wire terminals and W is the impedance of the balancing network'.*
BALANCING NETWORK. 'A network designed to simulate the impedance presented by a line or another network'.*

CCITT. Comité Consultatif International Télégraphique et Téléphonique = International Telegraph and Telephone Consultative Committee.
CENTRAL BATTERY SYSTEM. 'A system in which the whole of the energy for signalling and speaking is drawn from a power installation at the exchange'.*
CHANNEL TERMINAL EQUIPMENT. Equipment translating audio channels into a group of (usually 12) frequency division multiplex channels, and vice versa.
CHARACTERISTIC IMPEDANCE. 'Of a uniform transmission line. The impedance with which one end of the line must be terminated in order that the impedance presented at the other end shall have the same value as the terminating impedance'.*
CROSS-CONNECTION POINT. 'In the local cable network, equipment which enables, by use of jumper wires or equivalent, an incoming pair to be connected to any of the outgoing pairs'.**

DELAY. See: Propagation time.

ECHO. 'An echo is a wave which has been reflected or otherwise returned with sufficient magnitude and delay for it to be perceptible in some manner as a wave distinct from that directly transmitted'.*

ECHO-SUPPRESSOR. A voice-operated device installed in the four-wire part of a connection in order to suppress echoes, by inserting loss in the echo path.

EXCHANGE AREA. 'Area formed by the local exchange and the subscribers' lines'.**

EXTENSION LINE. A line connecting an extension station to a PBX.

FEEDING BRIDGE. A device installed in an exchange for supplying d.c. feeding current to the telephone set, and for separating the feeding circuit from the extending speech wires.

FEEDING LOSS. The decrease in sending sensitivity of a telephone set (expressed in transmission units) resulting from the insertion of the loop resistance of the subscriber's line.

FOUR-WIRE CIRCUIT. A circuit using different transmission paths (separated physically or in another way e.g. by using different frequency bands) for the 'go' and the 'return' channel.

FOUR-WIRE TERMINATING SET. 'An assembly of apparatus used to terminate the 'go' and 'return' channels of a four-wire circuit and to enable connection to be made to a two-wire circuit'.*

IMAGE IMPEDANCES. 'The two terminating impedances which are such that, when they are simultaneously connected to the appropriate terminals of the network, each terminating impedance is equal to the impedance presented to it'.*

INSERTION LOSS. 'The loss due to the insertion of a quadripole between two impedances Z_E (generator) and Z_R (load) is the expression in transmission units of the ratio $\frac{P_1}{P_2}$ where P_1 is the apparent power received by the load Z_R before the insertion of the said quadripole, and P_2 is the apparent power received by the load Z_R after the insertion of the said quadripole'.*

ITU International Telecommunication Union.

LISTENER ECHO. The echo, caused by twofold reflection on a telephone connection, received by the listener with some delay after the incident signal (see Figure 1.4).

LOCAL EXCHANGE. 'Exchange to which subscribers are connected'.**

LOCAL SYSTEM. See: Subscriber's local system.

LOOP RESISTANCE. The total d.c. resistance of the two conductors of a subscriber's line.

LOSS. See: Transmission loss.

NOSFER. Nouveau Système Fondamental pour la détermination des Equivalents de Référence = New fundamental system for the determination of reference equivalents.

A reference system specified by the CCITT for making subjective comparisons of telephone sets on the basis of loudness.

OBDM. Objectiver Bezugsdämpfungs Messer = Objective Reference Equivalent Meter (OREM).

PBX. 'Private Branch Exchange, a telephone exchange serving an individual organization and having connections to a public telephone exchange'.*

PRIMARY CENTRE. 'Centre to which local exchanges are connected and via which trunk (long-distance) connections are established'.**

PROPAGATION TIME. The time needed for the propagation of a signal from one point to another.

REFERENCE EQUIVALENT. The number of (surplus) decibels introduced in the reference system (NOSFER) to give the same loudness at the output of the receiver as the system under test, the acoustic pressure at the sending ends being the same in both cases (see Figure 1.3).

REFLECTION COEFFICIENT. 'A dimensionless measure of the degree of mismatch between two impedances given by the expression $(Z_b - Z_a)/(Z_b + Z_a)$, where Z_b and Z_a are the two impedances concerned.'* In the case of a transmission line with a characteristic impedance Z_a, terminated by an impedance Z_b, the (voltage) reflection coefficient is the complex ratio of the reflected signal voltage to the incident signal voltage at the termination.

RETURN LOSS. The expression in transmission units of the ratio $\left|\dfrac{Z_b + Z_a}{Z_b - Z_a}\right|$ as defined in reflection coefficient.

SENSITIVITY. The sensitivity of a microphone is the quotient of the electrical output, measured in a specified manner, and the sound pressure at the surface of the diaphragm.

The sensitivity of a telephone receiver is the quotient of the sound pressure produced and the electrical input, both quantities measured in a specified manner.

SIDETONE. 'The reproduction in a telephone receiver of sounds picked up by the associated microphone'.*

STABILITY. 'The maximum amount of gain, in addition to the working gain, that can be introduced into a circuit at any point equally and simultaneously in both directions of transmission without causing singing'.*

SUBSCRIBERS' LINES. 'The circuits connecting the subscribers' telephone sets' or PBX's 'to the local exchange'.**

SUBSCRIBER'S LOCAL SYSTEM. 'The subscriber's telephone set, the subscriber's line and the exchange feeding bridge form what is known as the subscriber's local system'.**

TALKER ECHO. The speech returned to the talker as an echo on a telephone connection (see Figure 1.4).
TELEPHONE BAND. The band containing the telephone-frequencies.
TELEPHONE-FREQUENCY. 'Any frequency within that part of the audio-frequency range essential for the transmission of speech of commercial quality, i.e. 300-3400 Hz'.*
TELEPHONE SET. 'An assembly of apparatus including a telephone transmitter, a telephone receiver, and usually a switch-hook and the immediately associated wiring and components'.*
TERMINATING SET. See: Four-wire terminating set.
(TRANSMISSION) LOSS. 'A general term used to denote a decrease in signal power in transmission from one point to another. Transmission loss is usually expressed in transmission units'.*
TRANSMISSION PERFORMANCE '(of a telephone circuit used for transmitting or reproducing speech). The effectiveness of the circuit for transmitting or reproducing speech in the circumstances in which it is used'.*
TRUNK CIRCUIT. 'A circuit connecting two exchanges in different localities'.*
TRUNK JUNCTION. 'A line connecting a trunk exchange to a local exchange . . .'*
TWO-WIRE CIRCUIT. 'A circuit formed of two conductors insulated from each other, providing a 'go' and 'return' channel in the same frequency band'.*

* Quotation from: *List of definitions of essential telecommunication terms.* Part 1, General terms, telephony, telegraphy (ITU, Geneva, 1961).
** Quotation from: CCITT Handbook *Local telephone networks*, Terminology (ITU, Geneva, 1968).

Note: In the above list, definitions are as much as possible in accordance with CCITT-practice and as published by the ITU. A number of terms also appears, with identical or essentially similar descriptions, in the '*International electrotechnical vocabulary*', Publication 50(55) of the IEC (Geneva, 1970).

Samenvatting

Na de belangrijke rol van de abonneeleiding in het telefoonnet te hebben geschetst, beziet de auteur in de Inleiding twee belangrijke transmissie-aspecten van de abonneeleiding, te weten de demping en de impedantie, in verband met hun effect op de luidheid van complete telefoonverbindingen en de stabiliteit van, en echo's op deze verbindingen. Aangetoond wordt dat een statistische aanpak gewenst is.
Hoofdstuk 2 geeft een analyse van statistische gegevens van abonneeleidingen, ontleend aan een door de Nederlandse PTT uitgevoerde landelijke steekproef. Het betreft met name de gegevens leidinglengte en lusweerstand. Een vergelijking van de kansverdeling van de leidinglengte met resultaten van soortgelijke onderzoeken in verschillende andere landen toont dat er in de meeste gevallen een opmerkelijke gelijkenis is.
Vervolgens wordt getracht de kansverdeling van de lengte te beschrijven met behulp van een analytische uitdrukking, waarbij een 'chi-kwadraat verdeling' een goede benadering blijkt op te leveren. In de verdere berekeningen wordt deze benadering gebruikt in een model van het abonneeleidingen-net.
Aan de hand van een beknopt overzicht van verschillende factoren die de kansverdelingen kunnen beïnvloeden, wordt getracht enig inzicht te krijgen in de geldigheid van de uit de steekproef verkregen resultaten op langere termijn.
Hierna bestudeert de auteur de zogenaamde 'vergelijkingsdemping' (reference equivalent) van de abonneeleidingen; de vergelijkingsdemping is een grootheid die aangeeft de demping voor de luidheid, bepaald door subjectieve vergelijking met een referentiesysteem. Ten behoeve van het bepalen van de verdelingsfunctie van de vergelijkingsdemping van abonneeleidingen wordt een methode ontwikkeld om uit de karakteristieken van de abonneeleiding de vergelijkingsdemping (luidheidsdemping) te berekenen. Ook de zogenaamde 'voedingsdemping' die ontstaat doordat de gevoeligheid van een koolmicrofoon afhankelijk is van de voedingsstroom, dient berekend te worden. Hiertoe wordt een model van de koolmicrofoon afgeleid, gebaseerd op de eigenschappen gemeten aan een aantal microfonen. Dit model kan tevens gebruikt worden om de invloed van variaties in het voedingssysteem na te gaan. Met behulp van de eerder gevonden verdelingsfunctie van de leidinglengte kan dan de uiteindelijke verdelingsfunctie van de vergelijkingsdempingen van abonneeleidingen voor zowel de ontvang- als de zendrichting worden bepaald.
In hoofdstuk 4 wordt eerst ingegaan op de waarden van de totale vergelijkingsdemping van complete telefoonverbindingen die wenselijk zijn, gezien de voorkeur van de gebruikers. Een vermindering van de spreiding van de in de praktijk optredende dem-

pingen blijkt zeer gewenst. Een aantal mogelijkheden om een dergelijke vermindering voor de abonneeleiding, inclusief het telefoontoestel, te verwezenlijken, wordt besproken. Enkele berekeningen betreffende de te bereiken resultaten met systemen van automatische dempingsregeling onder besturing van de lijn(gelijk)stroom worden uitgevoerd. Variaties in het voedingssysteem en in de componenten van de regelcircuits blijken het resultaat in aanzienlijke mate ongunstig te beïnvloeden.

Regelsystemen met stapsgewijze instelbare dempingen bieden voor de stabiliteit van de regelkarakteristieken betere vooruitzichten. Met een beperkt aantal stappen kan reeds een aanzienlijke vermindering van de spreiding in de vergelijkingsdempingen worden verkregen.

Geconcludeerd wordt dat in de spreiding van de vergelijkingsdempingen een eerste belangrijke verbetering, op redelijk korte termijn, zou kunnen worden gerealiseerd als de huidige koolmicrofoon zou worden vervangen door een nieuwe stabiele microfoon met ingebouwde versterker. Automatische regeling van de gevoeligheid in de telefoontoestellen is om verschillende praktische redenen niet aanbevelenswaard.

Voor de langere termijn verdient een systeem van stapsgewijze geschakelde dempingen in processor-bestuurde centrales overweging. Het inschakelen van de vereiste extra netwerken in de verbinding kan dan plaatsvinden onder besturing van de processor, die daartoe de benodigde criteria betreffende de abonneeleidingen in een geheugen heeft opgeslagen. In dit systeem heeft voor (zeer) lange abonneeleidingen het invoegen van versterking de voorkeur.

Hoofdstuk 5 behandelt de afsluitcondities van de abonneeleiding wat betreft hun invloed op de stabiliteit van verbindingen en het optreden van echo's. Mogelijkheden om de afsluitcondities te optimaliseren worden bestudeerd. Het met elkaar verbinden van de diverse delen van het tweedraads pad, zodanig dat de impedanties zijn aangepast, wordt bezien, maar blijkt niet tot een praktische oplossing te voeren. Hetzelfde geldt voor een afsluitimpedantie waarvan de waarde afhankelijk is van de leidinglengte.

Uit operationele overwegingen is een uniforme afsluitimpedantie gewenst, wat uiteraard een compromis inhoudt. Voor het bepalen van de optimum waarde voor een dergelijke uniforme impedantie wordt het begrip 'gewogen echodemping' ingevoerd, een grootheid waarin zowel de kansdichtheid van de bij de verschillende leidinglengten behorende resultaten, als een weging van de betekenis ten aanzien van echo en stabiliteit een rol spelen.

Praktische realiseringen van de op deze wijze afgeleide optimum afsluitimpedantie worden onderzocht. Het blijkt dat in het Nederlandse telefoonnet (met een impedantiebasis van 800 Ω) een uniforme afsluitimpedantie voor abonneeleidingen met een waarde van 600 Ω (de internationaal genormaliseerde waarde) – als een eerste stap – goede resultaten oplevert; een gemiddelde toename in de echodemping in de orde van enkele dB's kan worden verwacht. Eventuele verdere verbeteringen kunnen worden verkregen door extra voorzieningen (bijvoorbeeld serie-zelfinductie) in de locale centrale aan te brengen.

Summary

After having sketched the important role played by the subscriber's line in a telephone system, in the Introduction, the author considers two principal transmission aspects of the subscriber's line, namely transmission loss and impedance, with regard to their effect on the loudness of complete telephone connections and the stability of, and echoes on such connections. It is shown that a statistical approach is desirable.

Chapter 2 contains an analysis of statistical data on subscribers' lines, derived from a nation-wide sample survey conducted by the Netherlands Postal and Telecommunications Services (PTT). These data mainly relate to line length and loop resistance. A comparison of the statistical distribution of the line lengths with the results of similar surveys made in several other countries shows that there is mostly a remarkable resemblance.

Next, attempts are made to describe the distribution of length by means of an analytical expression. A 'chi-square distribution' proves to be a good approximation. In the further calculations this approximation is used in a model network of subscribers' lines.

By means of a brief review of various factors which can influence the statistical distributions, it is tried to obtain some insight into the applicability of the results of the survey on a longer term.

The author then studies the 'reference equivalent' of the subscribers' lines; reference equivalent is a quantity indicating the loudness loss as determined by subjective comparison with a reference system. In order to determine the distribution function of the reference equivalent of subscribers' lines, a method is developed to calculate the reference equivalent (loudness loss) from the characteristics of a subscriber's line. Also the 'feeding loss' caused by the dependence of the sensitivity of a carbon microphone on the feeding current, should be calculated. To this end a model of the carbon microphone is derived, based on the properties measured for a number of microphones. This model can also serve for the study on the effect of variations in the feeding system. By means of the distribution function of line length found before, the ultimate distribution function of the reference equivalent of subscribers' lines can be determined for the receiving as well as the sending direction.

Chapter 4 first deals with the values of the overall reference equivalent of complete telephone connections desired in view of the preference of the users. A reduction in the dispersion of the values of reference equivalent found in practice, appears to be highly desirable. A number of possibilities to realize such a reduction is discussed for

the subscriber's line, including the telephone set. Some calculations are made concerning the results obtainable by automatic regulation of loss controlled by the (d.c.) line current. Variations in the feeding system and in the regulator components appear to have an appreciable, adverse effect on the results.
Regulating systems with step-adjustable loss offer better prospects with regard to stability of regulator characteristics. Even with a limited number of steps an important reduction in the spread of reference equivalent can be achieved.
The conclusion is that with regard to the dispersion of reference equivalent values a first, considerable improvement could be obtained within a reasonably short time if the present carbon microphone would be replaced by a new, stable microphone with built-in amplifier. For several practical reasons automatic regulation of the sensitivity in the telephone sets is not recommended.
On a longer term a system of step-adjustable loss in processor-controlled exchanges could be considered. In that case the insertion of the required additional networks into the connection could be effected under the control of the processor in the memory of which the required criteria of the subscribers' lines are stored. With this system it is preferred to introduce positive gain for (very) long subscribers' lines.
Chapter 5 deals with the terminating conditions of the subscriber's line as concerns their impact on the stability of connections and the occurrence of echoes. Possibilities of optimizing the terminating conditions are examined. Interconnection of the various parts of the two-wire path in such a way that impedances are matched is considered, but does not lead to a practical solution. The same applies to a terminating impedance, the value of which is dependent on line length.
From an operational point of view a uniform terminating impedance is desired, but, of course, this implies a compromise. In order to determine the optimum value of such a uniform impedance, the concept 'weighted return loss' has been introduced, a quantity in which both the probability density and a weighting for the relevance with regard to echo and stability of the results corresponding to various line lengths, play a role. Practical realizations of the optimum terminating impedance thus obtained are studied. It turns out that in the Netherlands telephone network (with a nominal impedance of 800 Ω) a uniform termination of the subscribers' lines with a value of 600 Ω (the international standard value) would–as a first step–yield good results; it is estimated that the average increase in return loss will be in the order of several dB's. Further improvements could be made by means of additional measures (e.g. series self-inductance) in the local exchange.

Curriculum vitae

Geboren 12 november 1930 te Amsterdam.
In 1948 eindexamen aan de 1e Christelijke HBS-B, te Amsterdam.
Daarna studie aan de Technische Hogeschool Delft, waar begin 1954 het diploma van elektrotechnisch ingenieur werd behaald.
Gedurende ruim een jaar (student-) assistent bij prof. ir. G. H. Bast.
In 1954 en 1955 werd de militaire dienstplicht vervuld.
Daarna werkzaam bij het Staatsbedrijf der PTT; thans bij het Dr. Neher Laboratorium belast met de leiding van de sector Transmissie.
Neemt deel aan het werk van diverse internationale studiegroepen, in hoofdzaak op het gebied van transmissieplanning en transmissiekwaliteit.

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Stellingen

ir. C. Bakker

1 Aan de transmissie-aspecten van de abonneeleidingen in een telefoonnet en de bijbehorende statistische eigenschappen dient de nodige aandacht te worden besteed, gezien de belangrijke invloed op de transmissiekwaliteit van het telefoonnet als geheel.

2 Het verdient aanbeveling bij het ontwerpen van nieuwe telefoontoestellen ook de impedantie van het toestel in de rusttoestand in beschouwing te nemen.

3 Het primaire doel van een automatisch telefoonnet is aan de gebruikers spreekverbindingen van goede kwaliteit ter beschikking te stellen. Daartoe dienen de eigenschappen van schakel-, signalerings- en transmissiestelsels in hun onderlinge samenhang te worden bezien. Dit geldt niet alleen voor een eventueel toekomstig geïntegreerd net.

4 Nadat veel aandacht is geschonken aan het vergezicht op de gouden bergen van een toekomstig geheel geïntegreerd digitaal telecommunicatienet, krijgt men thans in kringen van telecommunicatiedeskundigen terecht meer oog voor het minder zonnige, tussenliggende dal van de overgangssituaties.

5 In het huidige internationale transmissieplan hebben voor het vaststellen van de eigenschappen van complete telefoonverbindingen de in de transmissietechniek reeds lang gehanteerde begrippen 'relatief niveau' en 'ruisvermogen gerelateerd aan een punt van relatief nul-niveau' aan directe betekenis ingeboet. Wat betreft de invloed van ruis, verdient het aanbeveling de signaal-ruisverhouding mede in beschouwing te nemen.

6 Terecht wordt in het rapport van een in de Bondsrepubliek Duitsland van regeringswege ingestelde commissie voor de verdere ontwikkeling van het telecommunicatiesysteem herhaaldelijk gewezen op het belang van internationale standaardisatie van nieuwe vormen van telecommunicatie.

Kommission für den Ausbau des technischen Kommunikationssystems, *Telekommunikationsbericht* (Bonn, jan. 1976).

7 De jeugdigheid van de televisie-omroep in Nederland blijkt vaak op hinderlijke wijze uit het gemak waarmee van het voor de programma's aangekondigde tijdschema wordt afgeweken; dit in tegenstelling tot de werkwijze van de in dit opzicht meer volwassen radio-omroep.

8 Het bij werkzaamheden aan wegen plaatsen en handhaven van verkeersborden met extra snelheids- en andere verkeersbeperkingen, anders en langer dan logischerwijze uit de actuele situatie voortvloeit, heeft een ongunstige invloed op de verkeersdiscipline en dient derhalve te worden gehekeld.

9 Het is opmerkelijk dat voor een al sinds eeuwen bestaand, en ook thans nog veelvuldig toegepast systeem van dakbedekking, namelijk dat met dakpannen, ondanks herhaalde verbeteringen in de uitvoering, blijkbaar nog steeds geen algemeen toepasbare oplossing is gevonden voor het euvel dat na een flinke storm grote hoeveelheden dakpannen de hun toegedachte functie niet meer vervullen.

10 Het hanteren in de gedragswetenschappen van (blok)-schema's voor het beschrijven van allerlei intermenselijke processen, houdt het gevaar in dat aan buitenstaanders een éénduidigheid en gedefinieerdheid wordt gesuggereerd, welke (gelukkig) niet overeenkomt met de werkelijkheid.

11 Er is een markant verschil tussen de opmaak en verpakking van overhemden voor heren en die van kleding met ongeveer dezelfde functie voor dames.