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Transmission Design of Intertoll Telephone Trunks

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At the 1952 Minneapolis summer meeting of the A.I.E.E. a symposium on the nationwide toll switching plan went into such features as the fundamental plant layout, numbering plan, toll switching and automatic accounting equipments. The present paper is intended to round out this coverage of the plan with a further discussion of the transmission features.*

THE PROBLEM

In the new nationwide toll switching plan using switching machines the layouts of toll circuits and the routings of traffic will be quite different from that of the earlier plans which were based on manual switching. Individual calls can be switched so fast and cheaply that switching is no longer a limiting factor and circuits can be laid out and used in such a way as to obtain maximum economy with few, if any, limitations from the switching standpoint.

An example of these changes is given in Fig. 1 which shows in (a) the circuit groups which would be used to handle a given (assumed) flow of traffic on a manual basis and in (b) the groups which would be used to handle the same traffic on a dial basis. In (a) there are 44 different

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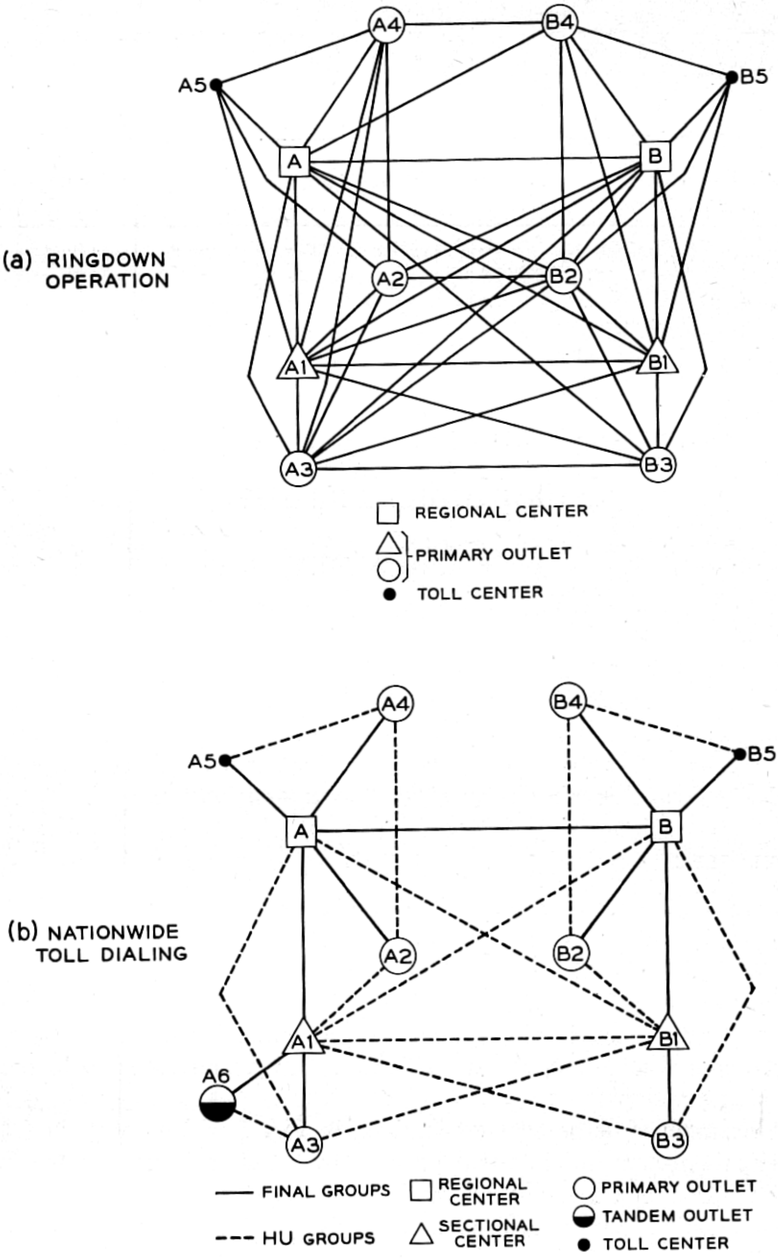

Fig. 1 — Typical intertoll trunk networks.

circuit groups and in (b) there are 26 circuit groups. More specific ideas regarding the effects of these differences can be obtained by considering how calls between specific centers (for example, A1 to B1) would be routed in the two plans.

From the transmission standpoint the principal impact of the new plan is that the situation will be changed from one in which as much of the traffic as practicable was handled over direct circuits with a minimum of switched traffic (circuits in tandem) to one in which two or more (up to a maximum of eight) circuits will be used in tandem on many calls and in which different numbers and make-ups of circuits may be encountered on successive calls between the same two telephones, as a result of the alternate routings employed with machine switching. This means that the losses of circuits must be low in order to provide adequate transmission on all calls and to avoid large differences in transmission on successive calls between the same two places.

The ideal method in such a situation would be to operate all circuits at zero loss since this would make the results independent of the number of circuits in tandem. However, the distances involved in the Bell System are so great that the propagation times, which affect echo, and the crosstalk between circuits require that even carrier circuits be operated at finite losses. Also, the plan must accommodate many voice frequency circuits on which the noise and singing conditions, as well as echo and crosstalk, may be more severe than on carrier circuits. The practical plan, therefore, is to:

1. Operate every circuit at the lowest loss practicable considering its length and the type of facilities used.

2. Assign circuits with different transmission capabilities in accordance with the parts they have to play in the operation of the over-all network.

The principal problem is to determine how low circuit losses can be made without getting into trouble due to one or more of the limitations mentioned above. This problem is complicated by the fact that the effects of these limitations are not directly proportional to circuit length or to the number of circuits in tandem. For example, if circuit (a) can be operated by itself at a loss of X db and circuit (b) can be operated by itself at a loss of Y db, the loss permissible when circuits (a) and (b) are switched together is less than $X + Y$. Ideally, therefore, each circuit should have a different loss in each different connection in which it is used. However, this is not practicable and a compromise must be adopted. This compromise provides that in some connections a particular circuit will operate at its lowest practical loss while in other connections higher losses will be employed to give over-all figures that will be adequate from the standpoint of echo, crosstalk, etc. The general procedure is as follows:

1. When a toll circuit is switched to another toll circuit at both ends work it at a loss which is called "via net loss" (VNL).

2. When the circuit is switched to another at one end only (the other end being at the point of origin or destination of the call) work it at a loss higher than VNL by an amount which we shall call "*S*" ("*S*" being a generic term derived from the fact that it may be associated with switching pads — usually called "*S*" pads).

3. When the circuit is used by itself (i.e., the origin and destination of the calls are at the ends of the circuit) increase its loss by "*S*" again — that is, work it at VNL plus 2*S*. This is known as "terminal net loss" (TNL).

Via net loss is, of course, to be the "lowest loss practicable" referred to above, and the next step is to establish methods of deriving VNL and of selecting the best value for "*S*".

Since it would be a very complicated process to work simultaneously with all four of the limiting factors mentioned above, (echo, crosstalk, singing, and noise), the practical approach has been to select one of them as the basis of design and then check the results against the other three, modifying the final solution as necessary so that all four are kept under control. Since long experience indicates that echo is likely to be the most difficult and complex factor to control, it has been used as the starting point in the solution of the problem. As will be evident later, there are a large number of solutions possible from the echo standpoint and the one which has been selected has been affected to a considerable extent by the other factors.

The next part of the material in this paper is, therefore, devoted to an analysis of circuit design from the echo standpoint.

DETERMINING LOWEST PRACTICABLE CIRCUIT LOSS FROM ECHO STANDPOINT

The over-all objective is to have practically no cases in which objectionable echo will be observed by customers.

If circuits could be precisely adjusted to the requirements in each different connection the probability of echo would be the same on all connections and the computations would have been carried out on the basis of a very small probability — say, 1 in 10,000. However, losses can be changed only in discrete steps (*S*) so that in a very large proportion of cases the losses will be higher than are theoretically necessary.

Hence it seems sensible to compute the theoretical losses on the more liberal basis of 1 in 100, relying on the excess loss in most connections to reduce the over-all probability to the very small value desired.

The echo problem with which we are concerned is illustrated in Fig. 2. As shown there, part of the speech power which is being transmitted to the listener "leaks" across the hybrid (or four-wire terminating set) at the listener's end and returns to the talker. This is known as "talker echo." Actually, of course, some of the echo which returns to the talker can leak across the hybrid there and go back to the listener. This is known as "listener echo." However, with modern plant listener echo will not be important if talker echo is adequately controlled.

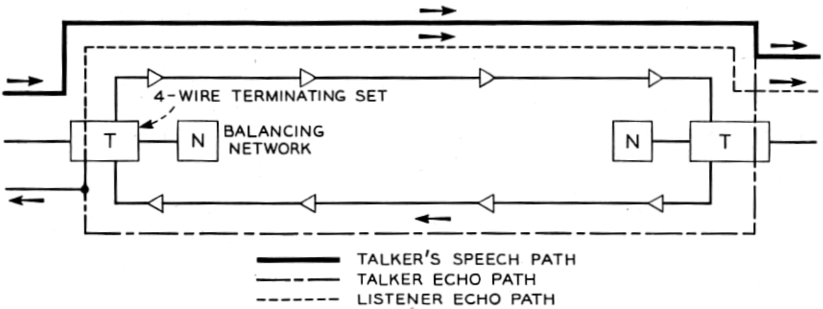

Fig. 2 — Echo paths.

Considering the effect of echo on the talker, if the elapsed time before the echo gets back to him is very short it is just like hearing his own voice through the sidetone in his own set, and unless it is very loud he doesn't notice it. If on the other hand, the elapsed time is long it sounds to him very much like the familiar acoustical echoes arising from physical obstacles. In extreme cases he may get the impression that the distant party is trying to interrupt him. The over-all effect of echo then depends on the following:

1. How loud it is — which in turn depends on how much loss there is in the echo path.
2. How long it is delayed before it gets back to him.
3. How easily he is annoyed by it (i.e., his "tolerance" to echo).

The factors involved are discussed in more detail in the following. For simplification four-wire circuits and four-wire switching are assumed; two-wire circuits and two-wire switching are treated as variations and are discussed later.

Tolerance to Echo

People vary greatly in their reaction to echo of given magnitude and delay and it is therefore necessary to treat them statistically, that is, what we need are the two statistical terms which are usually used to describe a mass of data, i.e., "average" and "standard deviation."

"Average" is simply the familiar algebraic average of the data — no talker is average but it is possible to obtain the average of a lot of talkers.

"Standard deviation" is a *number* which tells in general terms how the individuals spread out on both sides of the average. Usually: 30 to 35 per cent will be between the average and one standard deviation below the average; 30 to 35 per cent will be between the average and 1 standard deviation above it. At least 45 per cent will be between the average and two standard deviations below it and at least 45 per cent will be between the average and two standard deviations above it. Very few, if any, will be outside of plus or minus three standard deviations.

TABLE I

Round-Trip Delay (Milliseconds)	Loss in Echo Path Just Satisfactory to Average Observer
0	1.4 db
20	11.1 db
40	17.7 db
60	22.7 db
80	27.2 db
100	30.9 db

Judgment tests under controlled conditions and with a number of observers (talkers), under conditions simulating connections to subscribers near the toll office, have given the basic data on these effects in Table I. (These data are slightly different from some published earlier because of recent reevaluations. Further studies are now under way and may indicate some further changes.)

An analysis of all the test data indicated that the observer judgments conformed fairly well with a normal law curve having a standard deviation (D_0) of 2.5. This means, for example, taking the 40 millisecond delay condition, that while on the average a 17.7 db loss was required in the echo path to make the echo just tolerable, some 30 to 35 per cent of observers could tolerate 2.5 db less loss. Another 30 to 35 per cent were sensitive enough to need 2.5 more loss for satisfactory echo condition. Practically no observer was so sensitive as to require $3 \times 2.5 = 7.5$ db more than 17.7 db, and practically none was so tolerant that he could permit 7.5 db less.

Terminal Return Loss

As shown in Fig. 2, with four-wire switching and four-wire type circuits the only source of echo is lack of perfect balance between the balancing network of the four-wire terminating set (hybrid coil or its equivalent) and the trunk, loop, and subscriber station connected at the customer side of the set at the distant terminal. The ratio of the amount of power reflected back into the hybrid coil to the amount which goes on toward the listener can be expressed as a loss in db. This "terminal return loss" in the echo range (approximately 500 to 2,500 cycles) has been found by tests and computations to have an average value of 11 db and a standard deviation, $D_t = 3$.

Round-Trip Circuit Loss

The round-trip circuit loss plus the terminal return loss is the total loss in the echo path. The round-trip circuit loss, i.e., the over-all loss which the intertoll trunk (or trunks) inserts in the echo path, is the sum of the losses in the east-to-west and west-to-east directions. If the circuit regulation were perfect, this loss would simply be twice the nominal one-way loss of the trunks — which is the thing we are looking for.

However, regulation is not perfect, and in order to determine what the nominal loss should be we must take into account the deviations from it which are certain to occur in practice. A considerable amount of experience indicates that these deviations can be treated statistically and considering some improvement in maintenance methods and procedures and a wider use of carrier systems with improved regulation, a standard deviation of $D_v = 2$ db for round-trip losses seems a not unreasonable assumption for the next few years.

Relationship Between Working Echo Net Loss and Round-Trip Delay

We now have all of the data we need to solve our problem — which as stated before is to find what VNL to assign to a circuit of given length and on a given type of facility.

Our first step mathematically is to combine the three statistical distributions we have been talking about — i.e., tolerance to echo, terminal return loss and the variations in round-trip circuit loss.

The combined standard deviation (D_c) of the three sets of distributions is the square root of the sum of the squares of the standard deviations of the individual distributions. The first two distributions are independent of the number of links, N, (assuming four-wire switching) but the distribution of circuit loss variations is a function of the number of links. The mathematical expression for the combination of these three standard deviations is:

$$D_c^2 = D_o^2 + D_t^2 + ND_v^2$$
$$= 2.5^2 + 3^2 + N2^2$$

From this equation Table II can be constructed.

In line with the principles stated at the outset, the mathematics will be worked out on the basis that 99 calls out of 100 will be free from echo; then margins will be added. The mathematics are as follows: (1) In order to meet 99 per cent of the cases, 2.33 standard deviations must be used, or: Avg. Rd. Trip Loss = Avg. Echo Tol. − Avg. Ret. Loss + 2.33 Std. Dev. (2) The average one-way loss is the loss to be assigned and is one-half the average round-trip loss.

TABLE II

No. of Links	Standard Deviation
1	4.4 db
2	4.8 db
3	5.2 db
4	5.6 db
5	5.9 db
6	6.3 db
7	6.6 db
8	6.9 db

Permissible average losses with several different numbers of links, based on this equation, are given in Table III. These data are for four-wire circuits and four-wire switching. It will be noted from Table III that for a given total round-trip delay the necessary increase in over-all loss for increasing numbers of links varies somewhat for different conditions but for the more severe cases it is about 0.4 db per link.

Because, as stated at the outset, the relationship between round-trip delay and permissible circuit loss is not linear, Table III can not be used directly in selecting the working net loss of a circuit to be used in switched connections. An example will make this clear:

(a) From Table III, the permissible loss of a circuit with 20 ms round-trip delay is 5.0 db.

(b) If this were used as the basis for designing the circuit, the loss of four such circuits in tandem would be 20.0 db whereas the table shows that four links with a total round-trip delay of 80 ms could be operated at 14.6 db.

The problem then is to find the best method of determining "VNL" and "S". As indicated earlier, this problem has a wide variety of solutions among which the best can be selected on a judgment basis. The process is as follows:

(a) In Fig. 3 a solid curve is shown giving the relation between working loss and round-trip delay for a single link, the information being taken from Table III.

(b) With the plant as it will be in the reasonably near future the round-trip delay on any connection without an echo suppressor will not exceed about 45 ms. This figure is based on a survey of geographical lengths, with some adjustment for the expected more extensive use of carrier and taking into account the "rules" (discussed later) for the use of echo suppressors.

TABLE III

Total Round-Trip Delay (Milliseconds)	Permissible Working Over-all One-way Loss (db)			
	1 Link	2 Links	4 Links	6 Links*
0	0.3	0.8	1.7	2.5
20	5.0	5.6	6.5	7.4
40	8.5	9.0	9.8	10.6
60	10.9	11.4	12.3	13.1
80	13.2	13.7	14.6	15.4
100	15.1	15.6	16.5	17.2

* With the switching arrangements which will be used, not more than 6 intertoll trunks will be used in tandem without an echo suppressor.

(c) Then starting at any arbitrarily selected value of S, a straight line can be drawn from $2S$ (since there is S at each end) plus 0.4 (required to be added per link for variations) and intersecting the curve at 45 ms.

(d) In Fig. 3, three such straight lines are drawn, for $S = 1$, $S = 2$ and $S = 4$, which have slopes (in db per millisecond) about as follows:

S	Slope (db/ms)
1	0.15
2	0.10
4	0.016

(e) From these data, equations for VNL and TNL for four-wire circuits can be worked out in terms of round-trip delay, "d," thus:

S	VNL	TNL = VNL + $2S$
1	0.15d + 0.4	0.15d + 2.4
2	0.10d + 0.4	0.10d + 4.4
4	0.016d + 0.4	0.016d + 8.4

The slopes of the lines can be converted into factors (called "via net loss" factors — VNLF) in terms of db per mile by dividing twice the slope by the velocity of propagation in miles per millisecond. The product of VNLF and circuit length in miles plus 0.4 gives VNL. As an example, for K carrier circuits with a velocity of propagation of 105,000 miles per second, the via net loss factor for $S = 2$ would be $(2 \times 0.10) \div 105 = 0.0019$.

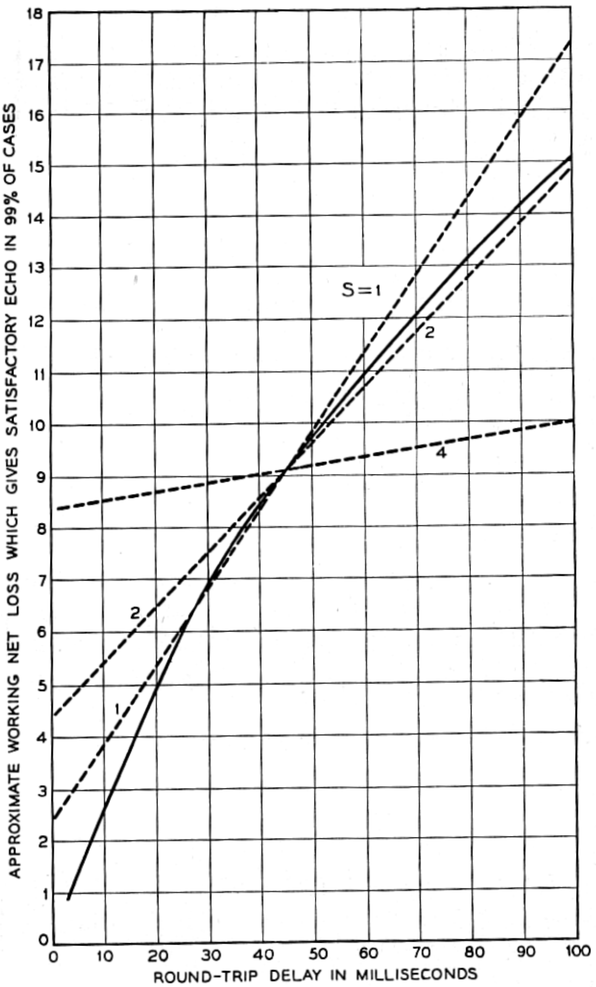

Fig. 3 — Approximate relationships between round-trip delay and permissible working one-way loss for an intertoll trunk from echo standpoint for four-wire circuits and four-wire switching.

For two-wire circuits the local echo paths at the repeaters make it impracticable to establish a straightforward relationship between over-all delay and echo performance. The via net loss factors for such circuits are approximations based on judgment and experience.

SELECTION OF VIA NET LOSS FACTORS AND S

From the foregoing, it is evident that the values of S and VNLF are interrelated and that there is a wide variety of possible relationships.

Fig. 3 shows that, up to fairly long delays, the lower the value of S, the lower the over-all losses at which the circuits can be worked from the echo standpoint.

Since the lower delay calls are much more numerous than longer delay calls, it is desirable to use as low an S as is practicable. However, in selecting a value, the other factors which have been neglected to this point — crosstalk, singing and noise — must now be taken into account and we must be sure that echo margin is now added. Each of these factors is discussed separately in the following.

Singing

The more extensive use of carrier reduces the importance of singing because voice frequency circuits are becoming shorter, thus eliminating the difficult singing problems associated with multi-repeater-section two-wire circuits. On the other hand, some of the conditions at circuit terminals may become more severe from the singing standpoint.

Studies indicate that over-all losses obtained with $S = 2$ are adequate to care for singing under most conditions but that if $S = 1$ were adopted, singing would be more important. With $S = 2$ the necessity for increasing circuit losses to avoid excessive danger of singing will probably be confined to a few open wire circuits having large discrete irregularities.

Noise

Noise is usually not a factor in the assignment of circuit losses. Carrier systems are designed so that under normal conditions the noise is low enough so that any desired loss can be used. If, in a specific case, noise in either carrier or voice frequency circuits is too high, the approach is to get rid of it by one or more of the means available.

Echo Margin

Reference to Fig. 3 will indicate that for $S = 2$ there is 2 db or more round-trip echo margin in all cases with round-trip delays less than the

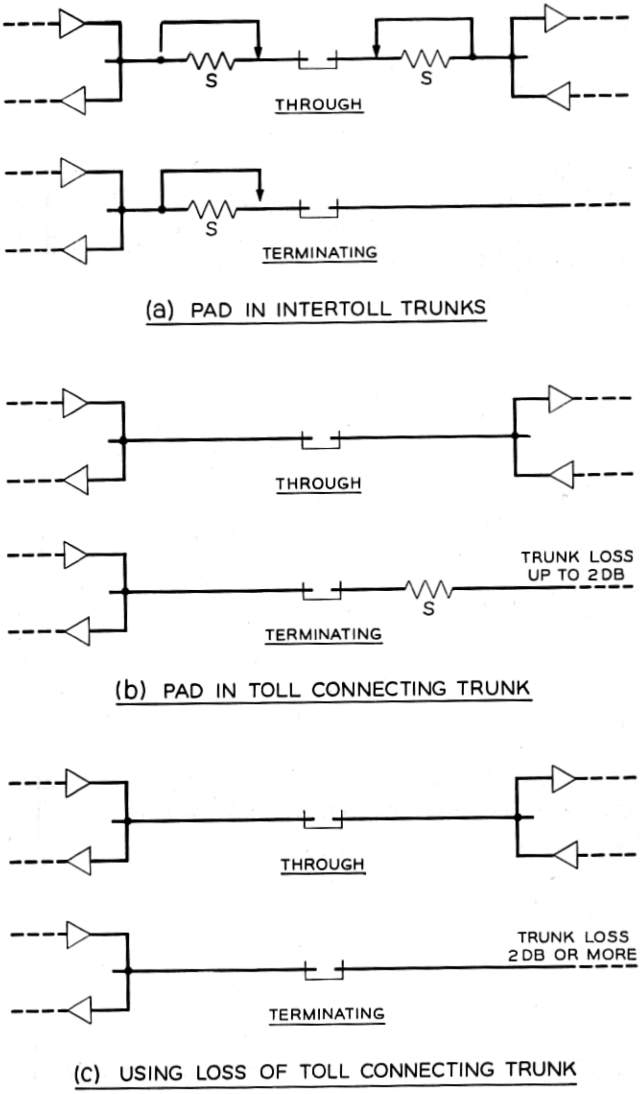

Fig. 4 — Methods of providing "*S*".

order of 30 or so milliseconds. With $S = 1$ there is little margin and with $S = 4$ there is excessive margin.

There will be very few connections with delays greater than about 30 milliseconds — which is roughly 1,500 miles of carrier — without echo suppressors. While the effect of the margin on probability of observing echo is difficult to compute quantitatively, it is estimated that with $S = 2$ this probability will be very small. Additional margin is also provided by the fact that on many connections the connecting trunk loss at the talker's end is greater than the loss used in the tests for establishing the echo tolerance curve.

Crosstalk

Analysis of many situations indicates, again, that with $S = 2$ the losses are about as low as are practicable in general from the crosstalk standpoint. With $S = 1$, they would be too low in many cases, and with $S = 4$, they would be unnecessarily high.

With $S = 2$, there may be a few cases where specific attention to crosstalk will be needed, particularly in open wire.

Final Selection

From the consideration of factors like the foregoing the value of 2 db has been selected for S on a judgment basis.

PROVISION OF S

The loss S can be provided in any of the following ways as appropriate. (See Fig. 4.)

1. As a switchable loss pad in the intertoll trunks.
2. As a fixed loss pad in the toll connecting trunk.
3. As part of the conductor loss of toll connecting trunks. This can be done only if the structural return loss of the connecting trunks against the balancing network is reasonably good.
4. If there is to be no switching to other intertoll trunks or to connecting trunks with more than 2 db loss, S may be provided simply by increasing the circuit loss by 2 db.

VIA NET LOSS FACTORS

Table IV lists typical VNLF's of Bell System intertoll trunk facilities for the condition $S = 2$. Typical losses at which circuits would be worked with $S = 2$ and with the via net loss factors tabulated in Table IV

TABLE IV — TYPICAL VIA NET LOSS FACTORS

Facility	VNLF (db per mile)	
	2-Wire Circuits	4-Wire Circuits
19H-88-50	0.03	0.014
19H-44-25	0.02	0.010
O. W. Voice	0.01	—
O. W. Carrier	—	0.0017
K or N Carrier	—	0.0019
L Carrier	—	0.0015
Radio	—	0.0014

are given in Table V. The advantages of high velocity, four-wire circuits (carrier and radio) are obvious from these tables.

ECHO SUPPRESSORS

Even if the intertoll trunk plant of the Bell System were all carrier' the length of some connections would be so great that some method of controlling echo other than simply increasing circuit loss is desirable. Lower losses can be obtained on such connections through the use of an "echo suppressor," an electronic device which under control of the talker's speech currents places a high loss in the return path at the right time to intercept the return echo currents.

Echo suppressors perform very well so long as not many circuits equipped with them are connected in tandem and there is not too much time delay between them. With manual operation the switching is so limited that the chances of connecting circuits with echo suppressors in tandem are small and it has been practicable to apply echo suppressors on the basis of round-trip delay of the individual circuits. However, with dial operation it will be possible to establish connections which are long enough to require an echo suppressor but which are composed of circuits each too short to require an echo suppressor based on its round-trip delay. For example, an echo suppressor would not normally be used on a 500-mile carrier circuit, but if eight such circuits were connected in tan-

TABLE V

Type and Length of Trunk	VNL (db)	TNL (db)
50-mile N1 Carrier	0.5	4.5
50-mile 2-W H-88	1.9	5.9
200-mile 4-W H-44	2.4	6.4
500-mile K Carrier	1.4	5.4

dem giving a total length of 4,000 miles, an echo suppressor would be imperative, if over-all loss is not to be excessive.

It is not practicable to take care of this problem merely by reducing the delay time at which an echo suppressor is applied, since if this were done it is conceivable that eight circuits each with an echo suppressor might be connected in tandem. It has been necessary, therefore, to establish more or less arbitrary rules to insure at least one echo suppressor on long connections and to make it very improbable that more than two will be encountered. In general, these rules specify that echo suppressors will be placed on:

a. All RC-NC circuits.

b. All RC-RC circuits.

c. On high-usage group circuits when the desired losses can not be met without them.

Our ideas as to when suppressors of Item c will be required may change with the trend from voice-frequency towards high-velocity carrier circuits. Experience will be a valuable guide, for it is not likely that an intolerable situation will build up overnight and without casting some shadow of coming echo; and the echo suppressor, being a discrete equipment unit, can be installed after it is found to be needed without appreciable lost motion or additional cost.

ALLOCATION OF FACILITIES

If the intertoll plant were homogeneous the over-all problem would be solved at this point — each circuit would be designed in accordance with the preceding and that would be that.

But the plant is not homogeneous — it consists of everything from loaded voice frequency circuits to circuits on microwave radio with VNLF's ranging from 0.03 to 0.0014. It is, therefore, necessary to allocate these facilities among different circuit groups in such a way that as far as practicable the higher performance facilities are used in the more demanding parts of the network.

As an aid to allocating facilities, charts like Fig. 5 are used. This chart shows ranges of losses within which circuits in different parts of the network are expected to fall. The losses shown there are exclusive of S which must be added, as indicated before, at both ends of each connection. It should be emphasized that these losses are not "limits" in the usual sense, neither are they attempts to divide up over-all losses among circuits. They simply help in allocating facilities in the nonhomogeneous plant among different circuit groups. As the use of carrier is extended, the plant will become more homogeneous and the need for such charts will gradually disappear.

Fortunately, from the transmission standpoint, while the machines will set up a wide variety of connections, the routing patterns will be rigidly controlled. Thus, it is practicable to know for each circuit group the maximum number of other circuits with which it can be used in tandem. The lower velocity circuits, two-wire circuits, narrow band circuits, etc. can (within practical limits) be allocated to groups which have relatively easy requirements.

TWO-WIRE SWITCHING — OTHER CONSIDERATIONS

Present views are that even the ultimate plan will involve two-wire switching at many points, mainly at the smaller switching points where

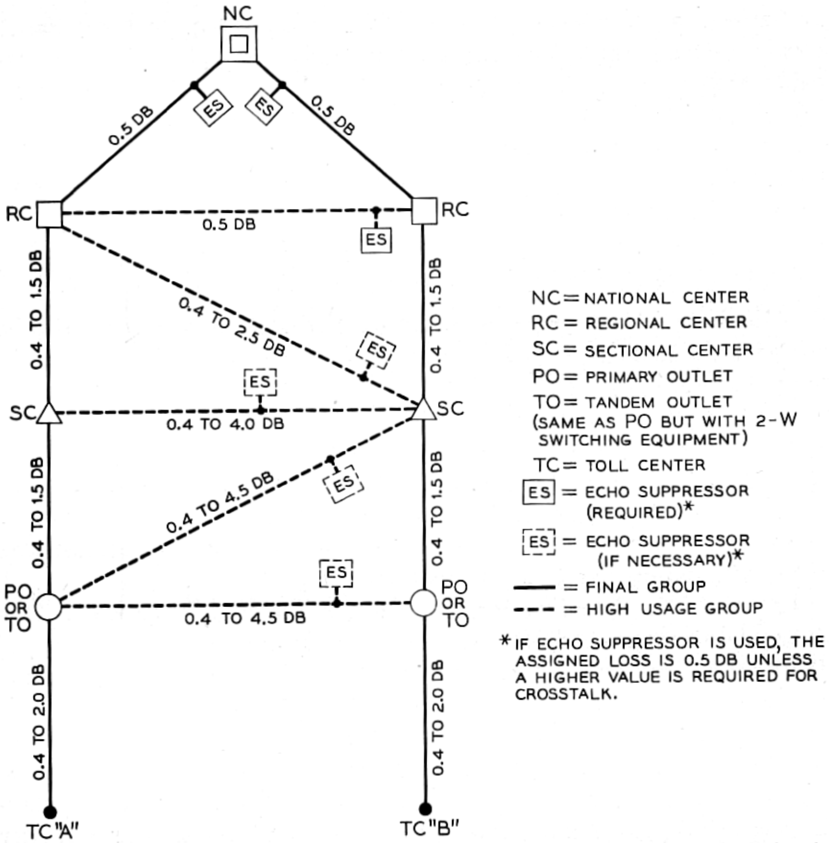

Fig. 5 — Intertoll routing pattern between two regions showing typical circuit groups.

the amount of traffic will not support the cost of complete automatic alternate routing features. This will cause some additional complication, for each such point introduces another source of echo due to the fact that the capacitance and resistance of the office cabling reduces the balance obtainable when two intertoll trunks are switched together. The effect of such switching on VNL's can be cared for by adding appropriate loss increments which will be small if a careful job of impedance matching is done and the distances from the toll terminal equipment to the switches is held within bounds.

No increment is added if the return loss for about 84 per cent of the circuits in the group is 24 db or more. These increments increase to about 0.2 db for a return loss of 20 db, 0.4 db for 18 db and so on. They are added to VNL of circuits between a two-wire switching point and a four-wire switching point and of circuits between two two-wire switching points. Impedance matching is usually accomplished by adding capacitance across the compromise network and in some cases across the shorter cable runs in an office.

All circuit losses referred to in this paper are 1000-cycle values, i.e., no allowance is made for the effects of noise and frequency distortion. Careful design, layout, and coordination of individual transmission systems are depended on to keep noise within proper bounds; and all new carrier systems going into the plant have transmitted bands wide enough to require no assignment of distortion transmission impairment (DTI). Circuits having excessive noise and those circuits with large DTI's are earmarked for improvement by any means that may come along. But beyond this, frequency distortion does not enter into VNL calculations since it can not be offset by reducing circuit losses without encountering trouble from the echo or other standpoint.

While we have considered only circuit design in this paper, it is evident that the success of the whole plan also depends on how closely circuit losses are maintained. This is important from two aspects.

1. The expected variations determine the allowance which must be made in the assigned loss. As indicated previously, it is expected that an allowance of 0.4 db per link will be adequate for the near future and it is hoped that as time goes on this figure can be reduced.

2. A more important factor is that unless circuit losses are maintained fairly precisely, large positive or negative excess losses can be accumulated on multi-switched connections. Avoidance of such large excesses is particularly important with dial operation since detection and avoidance of unsatisfactory transmission conditions by operators will be much less effective.

While the maintenance problem is at least as complex and difficult as the design problem, it is beyond the scope of this paper.

SUMMARY

To summarize the preceding discussion: For the particular conditions in the Bell System, a formula has been set up to give adequate approximations of the lowest practicable loss for practically all intertoll trunks as follows:

VNL = VNLF $\times$ $L + A + B$, where:

VNL = "Via Net Loss" (db) of the trunk.

VNLF = "Via Net Loss Factor;" i.e., a factor which depends on and is appropriate to the type of facilities used in the trunk.

L = Length in miles.

A = Design allowance for expected variations of circuit loss in service (0.4 db).

B = Amount to be added if two-wire switching is used; the magnitude depends on the passive return loss obtainable on such connections at the two-wire switching office.

At each end of the connection a loss of 2 db ($S = 2$) is added by appropriate means as discussed earlier.

CONCLUSION

Let it be emphasized that we have been talking largely of planning for the future in all that has preceded, for the switching plan as outlined is a growing thing and it will be a couple of years before much complex automatic alternate routing is done. And we would be very much surprised to escape growing pains and change of ideas as the plan develops. We are confident, however, that the plan is sound economically and transmission-wise; and flexible enough to adapt itself to further developments and experience.

ACKNOWLEDGMENT

As in most papers like this it would be prolix to mention all persons who took an active part in the preparation or in the development of the background data. But the author would be remiss if he did not call by name L. L. Bouton, who just prior to his recent retirement from Bell Telephone Laboratories, did much of the basic work on the mathematical concepts involved, on the simplification of these concepts for practical application, and on the re-evaluation of data that was required in these applications.