RECOMMENDATION ITU-R F.1192

TRAFFIC CAPACITY OF AUTOMATICALLY CONTROLLED RADIO SYSTEMS AND NETWORKS IN THE HF FIXED SERVICE

(Question ITU-R 147/9)

(1995)

The ITU Radiocommunication Assembly,

considering

a) the improvements available from the use of automatically controlled radio systems;

b) the limited amount of spectrum available for the HF fixed service (FS);

c) the demand for high reliability of HF FS;

d) the demand for high traffic throughput;

e) the demand for operation of networks in the HF FS;

f) that automatic systems should be able to cope with a wide range of traffic requirements and network size,

recommends

1 that, for automatically controlled HF radio networks, the methods described in Annex 1 are preferred for:

– the determination of the traffic throughput capacity;

– the estimation of the frequency requirements with respect to desired traffic throughput;

– the general planning of such systems;

– the comparison of the different types of system with respect to traffic throughput and frequency requirements.

ANNEX 1

Traffic capacity of automatically controlled radio systems and networks in the HF FS

1 Introduction

There are three basic automatically controlled radio systems. These are identified by the following acronyms:

ACC : asynchronous common channels

SCC : synchronous common channels

SSCT : synchronous separate calling/traffic channels

The ACC system asynchronously scans a set of pre-assigned channels in order to find a usable channel. Once a suitable channel is found, the traffic is sent over that channel; i.e. the calling and traffic channels are common.

The SCC system synchronously scans a set of pre-assigned channels in order to find a usable channel. Once a suitable channel is found, the traffic is sent over that channel; i.e. the calling and traffic channels are common.

The SSCT system synchronously scans a set of pre-assigned “calling” channels in order to make the initial contact. The call offers a number of candidate “traffic” channels. Having established the call, the two stations move to the candidate traffic channels and select the best.

There are two basic types of network which may utilize the above systems: multipoint and star.

2 Multipoint networks

The analysis given in this section is for a multipoint network where every station is equally loaded.

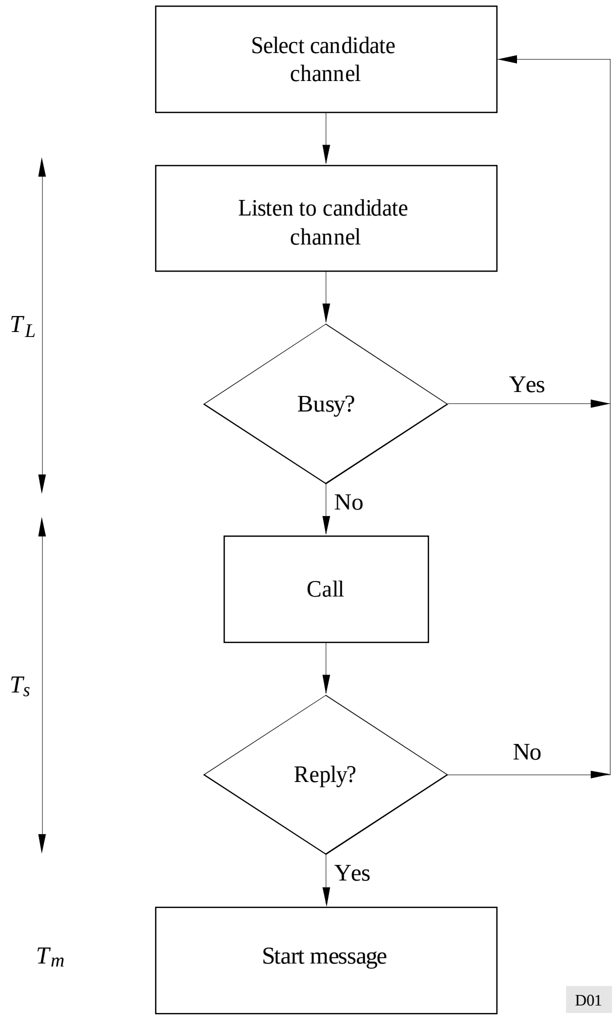
2.1 ACC system

2.1.1 Calling sequence

The ACC calling sequence is shown in Fig. 1.

FIGURE 1

ACC calling sequence



In the initial listening sequence, the station selects a candidate channel and checks that it is not occupied. There is a probability, P_1, that the channel is free. If busy, the station will select a second candidate channel and try again. The number of attempts, on average, will be $1/P_1$.

When the station transmits the call on the selected (free) channel, there are three probabilities that the call will be successful:

– the probability, P_2, that another station is not transmitting on that same channel,

– the probability, P_3, that the destination station is not already occupied,

– the probability, P_4, that the propagation conditions are good enough.

Expressions for P_1, P_2 and P_3 have been derived in Appendix 1.

The number of call attempts, i.e. transmissions, on average, is:

$$\frac{1}{\left(P_2\,P_3\,P_4\right)}$$

2.1.2 Traffic capacity

Let C: number of scanned channels

N: number of propagating channels

S: number of stations

E: traffic capacity (E) relating to a network of N channels and S stations

T_m: length of message (s)

T_s: scanning (or calling) time (s).

The number of messages/hour/station, M, is:

$$M = \frac{3\,600 \times E}{S\left(T_s / \left(P_2\,P_3\,P_4\right) + 2\,T_m\right)} \tag{1}$$

Each station will transmit M messages and receive M messages in 1 h.

There is a limit to how many messages an individual station can handle. Taking into account the amount of time that a station spends "listening" to check that the selected channel is free, and assuming that the maximum capacity of an individual station is E_{max} (E), the maximum number of messages/hour/station is:

$$M_{max} = \frac{3\,600 \times E_{max}}{\left(T_L / \left(P_1\,P_2\,P_3\,P_4\right) + T_s / \left(P_2\,P_3\,P_4\right) + 2\,T_m\right)} \tag{2}$$

where T_L is the listening time (s)

NOTE 1 – $2T_m$ is to take account of both received and transmitted messages.

NOTE 2 – The appropriate value for E_{max} is the subject of further studies.

2.2 SCC system

2.2.1 Calling sequence

The SCC calling sequence is shown in Fig. 2.

The SCC system has been assumed to be one which arranges a different order of listening out frequencies for each station (using an algorithm based on the station address).

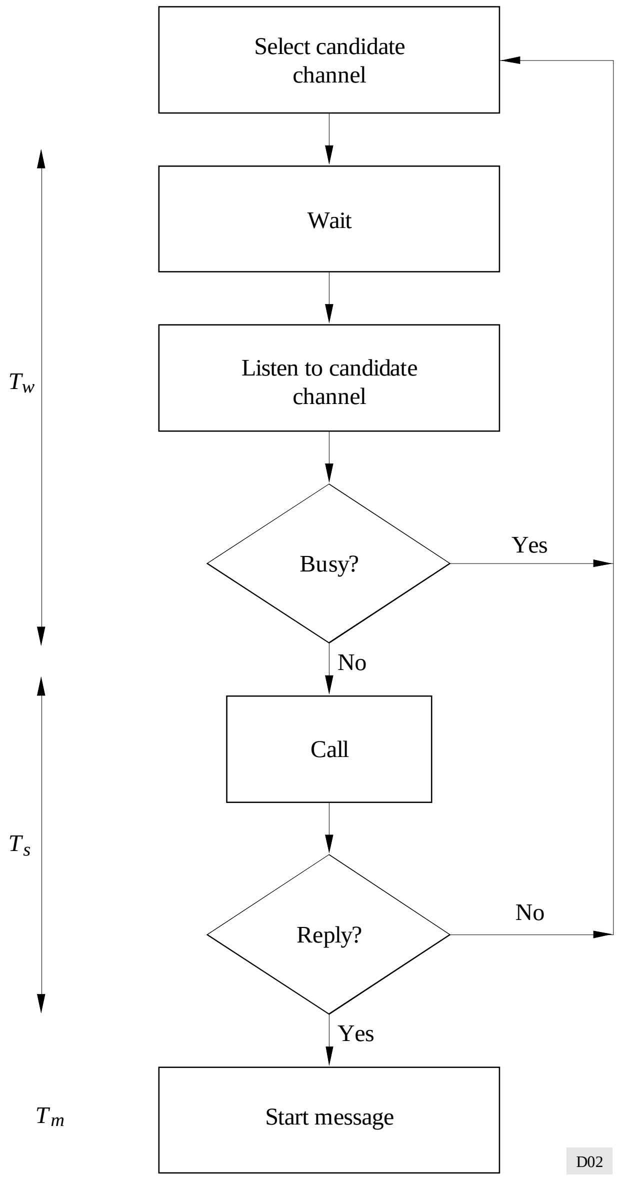
The station selects the candidate channel and then needs to wait (T_w) until the destination station selects that channel. Just before this occurs, the calling station must listen to ensure that the channel is free. Thus the station needs, on average, to wait: T_w/P_1 (s).

The calling sequence is similar to that of the ACC station except that T_s, the scanning time, is now much shorter as only one channel is "scanned".

If the system as described for the ACC is simply synchronized, the synchronized scanned channels effectively become a single channel and stations compete for it at the same time. This causes the system to lock-up at a certain point and therefore the system described above for SCC is preferred.

FIGURE 2

SCC calling sequence



2.2.2 Traffic capacity

The number of messages/hour/station, *M*, is the same as that for an ACC system (equation (1)).

For an SCC system:

$$M_{max} = \frac{3\,600 \times E_{max}}{\left(T_w / \left(P_1\, P_2\, P_3\, P_4\right) + T_s / \left(P_2\, P_3\, P_4\right) + 2\, T_m\right)} \tag{3}$$

2.3 SSCT system

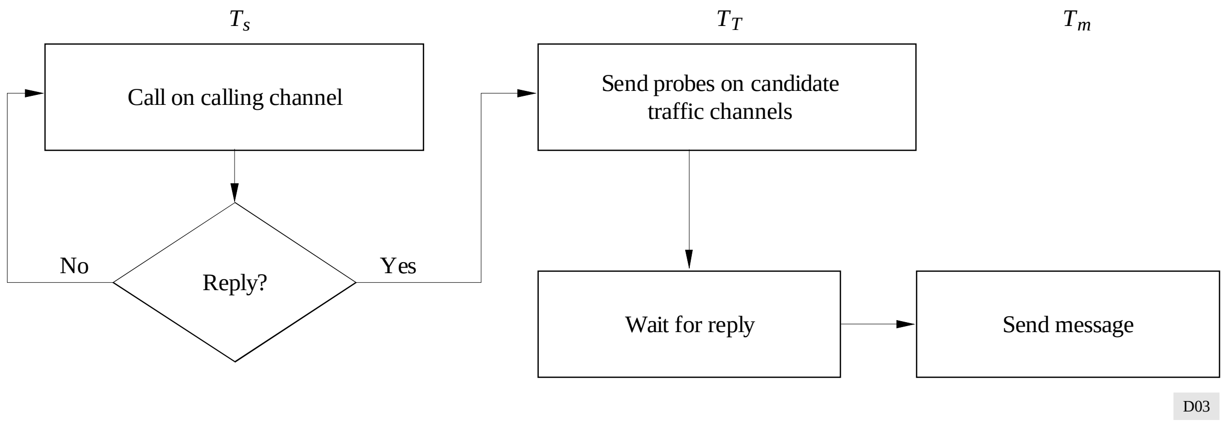
2.3.1 Calling sequence

The SSCT calling sequence is shown in Fig. 3. The synchronously scanned set of calling channels are equivalent to a "slotted Aloha" channel which has a capacity of 0.37 E. The probabilities P_1 and P_2 are taken into account in this way. However the probability P_3 must be considered.

When the destination station replies on the calling channel, both stations move to the traffic channels. The calling station sends a probe on each of the offered traffic channels and then waits for a reply on the preferred channel. This sequence will take T_T s.

FIGURE 3

SSCT calling sequence



2.3.2 Traffic capacity

Number of messages/hour/station, M, is:

$$M = \frac{3\,600 \times 0.37}{S\, T_s \,/\, P_3} \tag{4}$$

and:

$$M_{max} = \frac{3\,600 \times E_{max}}{T_s \,/\, P_3 + 2\left(T_T + T_m\right)} \tag{5}$$

3 Star networks

A star network consists of a central station with a number of outstations.

3.1 Outstations

As far as an outstation is concerned, the analysis and the values for M and M_{max} are the same as for a multipoint network (where S is the number of outstations).

3.2 Central station

If there are S outstations then the central station will need to handle 2 $M\,S$ messages in total. In order to achieve this, the central station will need to be able to handle a number of simultaneous radio channels. If the outstations are operating at full capacity, M_{max}, then S simultaneous radio channels will be needed at the central station in order to achieve full network throughput.

If the outstations are not at full capacity, M, then fewer simultaneous radio channels will be sufficient. The number of channels required at the central station, R, is given by:

$$R = \frac{M\,S}{M_{max}} \tag{6}$$

For ACC and SCC systems:

$$M = \frac{3\,600 \times E}{S\,T'_m} \tag{7}$$

where:

T'_m: time spent transmitting a message

$T'_m = T_s/(P_2\,P_3\,P_4) + T_m$

For a station operating at full capacity:

$$M_{max} = \frac{3\,600 \times E_{max}}{T_{tot}} \tag{8}$$

where T_{tot} is the total time that a station is occupied.

For ACC systems:

$$T_{tot} = T_L / \left(P_1\,P_2\,P_3\,P_4\right) + T_s / \left(P_2\,P_3\,P_4\right) + 2\,T_m \tag{9}$$

For SCC systems:

$$T_{tot} = T_w / \left(P_1\,P_2\,P_3\,P_4\right) + T_s / \left(P_2\,P_3\,P_4\right) + 2\,T_m \tag{10}$$

Thus:

$$R = \frac{E}{E_{max}} \times \frac{T_{tot}}{T'_m} \tag{11}$$

It should be noted that this is not strictly accurate as the outstation will experience lower values of P_1, P_2 and P_3 because they are addressing a central station which is running at full capacity. The result given by the above, however, is practical.

For an SSCT system:

$$R = \frac{0.37}{E_{max}} \times \frac{\left(T_s / P_3 + 2\left(T_t + T_m\right)\right)}{T_s / P_3} \tag{12}$$

4 Basic assumptions

For assessments of traffic capacity and system performance, the following assumptions are appropriate.

4.1 Message

A standard "page" of 20 lines of 69 characters per line, may be assumed (1 380 characters).

The message time, T_m, may be calculated assuming 7 bit/character, 50% FEC and 10% repeats (i.e. $1\,380 \times 7 \times \frac{1}{0.5} \times 1.1 = 21\,252$ bit/message).

It may also be assumed that every station in the network transmits and receives the same number of messages per hour, M.

4.2 Probability of propagation, P_4

This is a measure of the success of the system in selecting the candidate channel in the ACC and SCC systems. A figure of 63% has been measured in test systems and this figure has been used for P_4.

4.3 Scanning time, T_S, ACC

A scanning time T_S may be assumed.

$$T_S = t\,(2\,C + 9) \tag{13}$$

where:

$t = 0.392$ s

C: number of scanned channels.

4.4 Listening time, T_L, ACC

It may be assumed that an ACC station listens for a time equal to the channel scanning time, in order to check that a channel is free.

4.5 Waiting time, T_W, SCC

If the network has C allocated channels then, on average, the waiting time will be:

$$T_W = C / 2 \times T_S \qquad \text{s} \tag{14}$$

where T_S is the synchronous scanning time.

4.6 Traffic channel set-up time, T_T, SSCT

For an SSCT system which offers five traffic channels in its initial call, the following procedure may be assumed. Calls are sent, sequentially, by the calling station which then listens, in turn, on each channel for a reply. The called station replies on the "best" channel but its algorithm is biased to select the first offered channel which is the most favoured channel according to the calling station. On average the calling station would wait $2.5 \times T_S$ (s) for the reply, but the bias causes this to be $1.5 \times T_S$ in practice.

Therefore:

$$T_T = (2.5 \times 2 + 1.5)\,T_S = 6.5 \times T_S \qquad \text{s}$$

5 The results of traffic calculations

From the results of calculations which considered the full range of diurnal, seasonal and solar cycle variations in propagation conditions, and a wide range of data rates and network sizes, the following conclusions were drawn.

5.1 ACC

As the number of propagating channels is increased the performance of the network does not necessarily improve. For example, for a data rate of 1 200 bit/s, 6 channels perform better than 14 if the network consists of less than 30 stations. Ten channels give a better performance than 14 channels up to 100 stations. This effect tends to be more pronounced for the higher data speeds.

For small networks of 10 or less stations, the choice of the number of allocated channels is quite complicated but there is no advantage in allocating too many.

Increasing the length of the message to two pages does not change the relative performance of the network with respect to the channels. The system is slightly more efficient with the longer messages in that just over half the number of messages are transmitted and received per station compared with the one page message length.

5.2 SCC

Similar to the ACC results, the SCC system also shows that the performance for 10 channels generally exceeds that of 14, and that 6 channels is often better than 14. Also for networks of 10 or less stations, it is wasteful to allocate too many channels as the performance tends to be as good with fewer channels.

Increasing the length of the message to two pages does not change the relative performance of the network with respect to the channels. The system is slightly more efficient with the longer messages in that just over half the number of messages are transmitted and received per station compared with the one page message length.

5.3 SSCT

The performance of the SSCT system becomes better as the data speed is increased, the message becomes longer and the number of scanning channel sets is increased.

The effect of longer messages is particularly interesting because, as the system is capable of setting up a particular number of calls, determined only by the scanning rate, then the number of messages/hour/station, M, is almost the same for one and two page messages.

The effect of two calling channel sets is to double the throughput.

5.4 Discussion

For networks consisting of a few stations, say 15 or less, there is no particular advantage in any of the systems. As the network increases in size the SCC and the SSCT systems show a marked improvement over the ACC.

At the lower data speeds the SSCT system shows a better performance than SCC but the 2 systems show similar performance at the higher data speeds (SCC with 10 propagating channels). The SSCT is significantly better as the message length increases or if 2 calling channel sets are used.

Both ACC and SCC systems need careful planning as the number of scanned channels is of prime importance. Frequency management is very necessary as if too many channels are scanned the performance can suffer. In planning systems based on SCC and ACC the future expansion possibilities need to be carefully considered. An increase in the number of stations could change the number of frequency channels required for optimum performance.

6 Conclusion

The formulas and results derived in this Annex can be used as a planning tool. It is possible to predict the expected performance of an automatically controlled radio system and also to realise the limitations of a such a system.

APPENDIX 1

TO ANNEX 1

Calculations of probabilities relating to clashing and occupied channels

1 Probability P_1 that selected channel is free – ACC and SCC

In 1 h the total number of messages/channel/s:

$$m = \frac{M\,S}{3\,600\,N} \tag{15}$$

where:

M: messages/hour/station

S: No. of stations

N: No. of channels.

Let the time that a message occupies a channel be T'_m (s).

The probability of K new messages during time interval t is given by the Poisson distribution:

$$P\,(K) = (mt)^K \; e^{-\,mt} / K! \qquad K \geq 0 \tag{16}$$

where m is the average message rate.

A channel is free as long as no other station began a message T'_m (s) previously, or starts one within the next T'_m (s). Thus, the probability of there being no messages ($K = 0$) in time $2T'_m$ is the probability that the channel is free.

From equation (16):

$$P(0) = \exp\left(-\,2\, m\, T'_m\right)$$

$$= \exp\left(-\frac{2\, M\, S\, T'_m}{3\,600\, N}\right) \tag{17}$$

Now:

$$M = \frac{3\,600 \times E}{S \times T'_m} \tag{18}$$

where E (E) is the total network traffic capacity.

Thus:

$$P_1(0) = \exp\left(-\,2\, E / N\right) \tag{19}$$

1.1 Case of ACC station

When an ACC station is at full capacity

$$M_{max} = \frac{3\,600 \times E_{max}}{t_1 + t_s + 2\, T_m} \tag{20}$$

where:

t_1: total listening time $(T_s / (P_1\, P_2\, P_3\, P_4))$

t_s: total scanning time

$$t_s = \frac{T_s\,(2\, C + 9)}{\left(P_2\, P_3\, P_4\right)} \tag{21}$$

C: No. of channels

T_m: time of the message.

Now:

$$T'_m = t_s + T_m$$

and:

$$P_1 = \exp\left(-\frac{2 \times E_{max}\left(t_s + T_m\right) S}{N\left(t_w + t_s + 2\, T_m\right)}\right) \tag{22}$$

1.2 Case of SCC station

When an SCC station is at full capacity:

$$M_{max} = \frac{3\,600 \times E_{max}}{t_w + T_s + 2\,T_m} \tag{23}$$

where:

t_w: total waiting time $(T_s / (P_1\, P_2\, P_3\, P_4))$

and:

$$P_1 = \exp\left(- \frac{2 \times E_{max}\left(T_s + T_m\right) S}{N\left(t_w + T_s + 2\,T_m\right)} \right) \tag{24}$$

2 Probability P_2 that no clash occurs on a selected channel – ACC/SCC

The station listens before attempting to transmit on the selected channel. Thus a channel is free as long as no other station generates a message within time T_m.

Thus, similar to equation (19):

$$P_2(0) = \exp\left(- E / N\right) \tag{25}$$

and similarly, for the condition when the station is at full capacity:

For ACC station:

$$P_2 = \exp\left(- \frac{2 \times E_{max}\left(t_s + T_m\right) S}{N\left(t_1 + t_s + 2\,T_m\right)} \right) \tag{26}$$

For SCC station:

$$P_2 = \exp\left(- \frac{2 \times E_{max}\left(t_s + T_m\right) S}{N\left(t_w + t_s + 2\,T_m\right)} \right) \tag{27}$$

3 Probability P_3 that the destination station is free

Each station has $2M$ messages per hour (M transmitted and M received).

Therefore each station deals with $2M/3\,600$ messages per second.

A station is free as long as no messages are transmitted or received during T'_m previously or within the next T'_m where T'_m is the total time a station is occupied with a message.

Thus the probability of being free $P_3(0)$, is:

$$P_3 = \exp\left(- \frac{2\,M\;2\,T'_m}{3\,600} \right) \tag{28}$$

3.1 For an ACC station

A transmitted message takes time $t_1 + t_s + T_m$

Hence total occupied time:

$$2\,T'_m \;=\; t_1 \;+\; t_s \;+\; 2\,T_{m1} \tag{29}$$

Now:

$$M \;=\; \frac{3\,600 \;\times\; E}{s\left(t_s \;+\; T_m\right)} \tag{30}$$

and:

$$P_3 \;=\; \exp\left(-\frac{2 \;\times\; E\left(t_1 \;+\; t_s \;+\; 2\,T_m\right)}{N\left(t_s \;+\; T_m\right)}\right) \tag{31}$$

When at full capacity:

$$M \;=\; \frac{3\,600 \;\times\; E_{max}}{\left(t_1 \;+\; t_s \;+\; 2\,T_m\right)}$$

$$=\; \frac{3\,600 \;\times\; E_{max}}{2\,T'_m} \tag{32}$$

and:

$$P_3 \;=\; \exp\left(-\,2 \;\times\; E_{max}\right) \tag{33}$$

3.2 For an SCC station

A transmitted message takes time $t_w + t_s + T_m$ and a received message occupies time T_m.

Hence total occupied time:

$$2\,T'_m \;=\; t_w \;+\; t_s \;+\; 2\,T_m \tag{34}$$

Now:

$$M \;=\; \frac{3\,600 \;\times\; E}{s\left(t_s \;+\; T_m\right)} \tag{35}$$

and:

$$P_3 \;=\; \exp\left(-\frac{2 \;\times\; E\left(t_w \;+\; t_s \;+\; 2\,T_m\right)}{N\left(t_s \;+\; T_m\right)}\right) \tag{36}$$

When at full capacity:

$$M \;=\; \frac{3\,600 \;\times\; E_{max}}{\left(t_w \;+\; t_s \;+\; 2\,T_m\right)}$$

$$=\; \frac{3\,600 \;\times\; E_{max}}{2\,T'_m} \tag{37}$$

and:

$$P_3 \;=\; \exp\left(-\,2 \;\times\; E_{max}\right) \tag{38}$$

3.3 For an SSCT station

$$M = \frac{3\,600 \times 0.37 \times C_s}{S\,T_s / P_3} \tag{39}$$

where C_s is number of calling channel sets

and:

$$P_3 = \exp\left(-\frac{4\,T_m' \times 0.37 \times C_s \times P_3}{S\,T_s}\right) \tag{40}$$

where $T_m' = (6.5T_s + T_m)$

i.e:

$$P = e^{-KP}$$

and hence, approximately $P' = 1 - KP'$

Thus:

$$P' = 1 / (1 + K) \tag{41}$$

where:

$$K = \frac{4\,T_m' \times 0.37}{S\,T_s}$$

and:

$$P_3 = \exp\left(-\frac{4\,T_m' \times 0.37 \times P_3}{S\,T_s}\right) \tag{42}$$

$$P_3 = \exp\left(-\frac{4\,T_m' \times 0.37 \times C_s}{S\,T_s + 4\,T_m' \times 0.37}\right) \tag{43}$$

When station is at full capacity:

$$M_{max} = \frac{3\,600 \times E_{max}}{2\,T_m'} \tag{44}$$

and:

$$P_3 = \exp\left(-2 \times E_{max}\right) \tag{45}$$

4 Practical calculations

The expressions for P_1, P_2 and P_3 derived above contain values such as t_l, t_w and t_s which in themselves contain P_1, P_2 and P_3. In calculating the values of t_l, t_w and t_s, nominal values of P_1, P_2 and P_3 are assumed. The calculated values for P_1, P_2 and P_3 are relatively unaffected by the variations in the assumed values used when calculating t_l, t_w and t_s. Values for P_1, P_2 and P_3 are therefore varied until a degree of compatibility is reached.