REPORT 741-3

MULTI-CHANNEL LAND MOBILE SYSTEMS FOR DISPATCH TRAFFIC (WITH OR WITHOUT PSTN* INTERCONNECTION)

(Question 37/8)

(1978-1982-1986-1990)

Introduction

Radio spectrum allocated for dispatch traffic is becoming increasingly congested and already many users (networks) have to share a channel with several other users. This practice employs the channel more effectively but gives the participants a reduced "grade of service" in the sense that they may often have to wait for some time for a channel to become free and they suffer from reduced privacy. Not only improved channel utilization but also better grade of service and good privacy conditions are important factors to design dispatch systems.

Part A of this Report deals with the general aspects of multi-channel land mobile systems for dispatch traffic, such as system configuration, characteristics of dispatch traffic, grade of service, traffic handling capability, performance of trunked systems, signalling and so on.

Part B of this Report introduces some systems being installed or planned by some administrations.

For this purpose of this Report, "dispatch system" has the meaning: A radio system used to control the operation of a fleet of mobiles, such as air craft, taxis, police, etc., and "trunked system" has the meaning: A multi-channel system with automatic channel selection, particularly referring to dispatch systems.

However, this Report does not consider the detail of interconnection of trunked dispatch systems with public or private switched telephone networks. Such interconnection requires further study.

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* Public switched telephone network.

PART A

GENERAL ASPECTS RELATING TO SPECTRUM CONSERVATION AND SYSTEM DESIGN

1. System configuration

A typical arrangement of equipment, covering a single radio zone, is shown in Fig. 1 and consists of the following four principal items:

- a number of control posts (CP)(s) (i.e. dispatchers or control stations), consisting of a CP(s), each connected to a switching centre, either by a dedicated line or a radio path using channel equipment (CE);
- a switching centre (SC), (several switching centres may be interconnected);
- a number of base stations (BS) each containing a number n of CE(s).
- a number of groups of mobile stations, each consisting of a_m Mobile Stations (MS) and each being served by its own CP.

To enable a CP to call one of its MSs, and vice versa, each CP and each MS is considered to have access to one of the radio channels by means of an access procedure which is still to be defined.

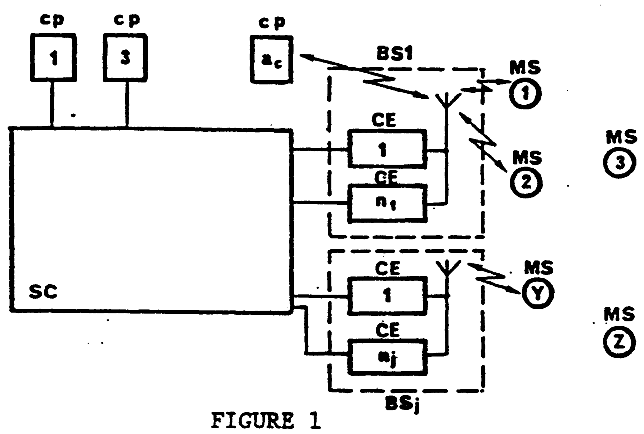

FIGURE 1

Arrangement of equipment in a trunked system

cp: control post (i.e. dispatcher or control station)

CE: channel equipment

MS: mobile station

a_c: number of control posts

SC: switching centre (several switching centres may be interconnected)

BS: base station (some administrations define the base station as one channel equipment)

$n = \sum_{k=1}^{j} n_k$: total number of channel equipment

2. Characteristics of dispatch traffic in private mobile radio systems

The increase in channel loading which can be achieved by trunking depends on the kind of traffic carried. Mobile radio dispatch traffic differs from public mobile telephony traffic in a number of ways:

- the mean holding time of calls is shorter (15 seconds may be typical);
- many users operate a vehicle fleet system where a single operator controls a number of mobiles;
- the size of fleets varies greatly.

2.1 *Fleet operation*

The number of users in the system is, in effect, equal to the number of CP operators, not the number of mobiles, because if the operator is busy nobody in the fleet can place a new call. Thus all the traffic of the fleet passes through the operator and a mobile radio system therefore is characterized by a small number of users (operators), some of which may offer large loads and some small. Such a system is termed "unbalanced" (see also § 5).

Fleet operation means that there are actually two kinds of queue. The CP operator only ever has to wait because the channel is occupied by another fleet (the "sharing" delay) but an MS may have to wait not only for other fleets but also because his own operator is busy with a call to another MS (the "fleet" delay). It can be argued that the fleet delay can be ignored because:

- it is experienced only by the MSs, each of which uses the system rather sparingly compared with the CP;
- the delay can be reduced only if the fleet owner is prepared to employ extra operators, a factor which is outside the control of the systems designer;
- the psychological effect of waiting while one's colleagues talk to the CP is not the same as that of waiting while strangers block the channel.

2.2 *Random fluctuations*

The random nature of mobile radio dispatch traffic means that the busy hour traffic level will fluctuate. The fluctuations can be surprisingly large and last for significant periods. Upward fluctuations in the traffic level will result in a reduced grade of service which will be unacceptable to the users if they occur too often or last too long. It may be desirable to protect against this with an 'overload' criterion of the form:

- the ordinary busy hour grade of service should not degrade by more than, e.g., a factor of 2 for periods longer than half an hour occurring no more than once every 20 days.

2.3 *Day to day traffic variations*

Telephony experience [Hayward and Wilkinson, 1970] shows that there will be variations in the mean busy hour traffic from day to day in addition to the random fluctuations. With small numbers of users the variations can be expected to be large: the traffic will vary not only because of changes in the activity of the whole community, but also because of sudden changes in the demand of just a few of the users. The day to day variations add to the random fluctuations and so, in practice, the safety margin required for protection against overload is likely to be significantly larger than consideration of the random fluctuations alone would indicate. At present the extent of these variations has not been studied.

2.4 Operating procedures

Operating procedures which may cause excessive simultaneous call requests from many mobile stations can overload the access protocol or the switching centre of a trunked system. For example, transactions in which a control post seeks to allocate work to mobile stations by means of a fleet call requesting offers or "bids" for the work. System design may make special provision for such procedures (see also Annex I to Part A, section 3.3).

3. Grade of service and traffic handling capability

The increase in channel loading that can be achieved with a trunked system also depends on the grade of service required.

3.1 *Reference system*

The merits of the trunked system with respect to traffic handling capacity and radio channel efficiency can be compared with those of a single channel reference system employing automatic sharing, having the same amount of traffic per MS and the same number of MSs per CP and offering the same grade of service.

It is assumed that a CP is connected to a SC by a dedicated line, and n is less than a_c.

3.2 *Traffic assumptions*

In addition to the usual assumptions for estimating the volume of the traffic in ordinary telephone networks, the following assumptions may be made:

- communication is possible, in two directions in a simplex mode, between a CP and each of its MSs, but not more than one at a time;
- any other communication, for example between MSs of the same or different networks or between CPs of different networks, is excluded;
- all calls are queued and processed in the order of arrival;
- any degradation due to multipath fading, interference and other deficiencies inherent in radio transmission is disregarded.

3.3 *Delay criteria*

Because of the relatively short mean holding times encountered in mobile radio networks for private use, the character of the messages and the general pattern of conduct of the user of such networks, a waiting system, also known as delay or queueing system, is desirable.

For the purpose of traffic calculations a delay criterion, both under normal traffic and overload conditions, may then be used as a measure of the grade of service in accordance with current telephone practices.

The following criteria are appropriate:

- under *normal traffic conditions* the probability of excess delay (P), that is, the probability that a given waiting time is exceeded, shall be limited. If, for example, this waiting time is one mean holding time, then $P = P_r$. It may also be desirable to guard against occasional very long delays;
- under *overload conditions* the probability of excess delay shall not be more than, for example, twice the probability under normal traffic conditions (e.g. P_r), in the case that the traffic per MS increases by a given percentage, for example 10%. An alternative way of specifying the overload criteria is given in § 2.2.

3.4 *Probability of excess delay in the single-channel reference system*

The distribution of waiting time in the theoretical model of one telephone line serving a finite number of traffic offering sources is known and has been published. It can be shown that the model of a single mobile radio network consisting of one CP and a finite number of MSs is equivalent to the telephone model mentioned above, with the CP corresponding to the line and the MSs corresponding to the traffic sources.

However, the single-channel reference system consists of several such networks, each comprising one CP and several MSs. As the CPs are linked by the fact that they have access to only one radio channel, it was necessary to also consider the CPs as traffic sources. Consequently, a single radio channel serving simultaneously several CPs and their MSs will give rise to two rows of queueing calls which are linked to each other.

An exact solution of the distribution of waiting times has not been obtained but an approximate solution by means of computer calculations shows that for a single-channel reference system consisting of 10 CPs, each serving 10 MSs with a traffic load of 0.005 erlang per MS, the probability, P_r, of the waiting time exceeding the mean holding time (e.g. 15s) is equal to about 0.3.

3.5 *Channel efficiency and overload capability of a trunked system*

From the results of similar, preliminary calculations performed on a trunked system with the same probability of excess delay, $P_r \approx 0.3$, as the single-channel reference system, the following simple empirical relationship between the number of CPs (a_c) and the number of radio-channels n (where $n > 1$), is derived:

$$a_c = \frac{n - 0.6}{a_m \, \alpha_m}$$

where

a_m : the number of MSs per CP

α_m : the traffic per MS in the busy hour, expressed in erlang.

When the number of radio channels is increased, the admissible number of CPs increases in accordance with the above formula. The channel efficiency expressed in terms of traffic load per channel also increases. This last relationship is shown in Fig. 2 under normal traffic conditions, for a probability of excess delay of about 0.3.

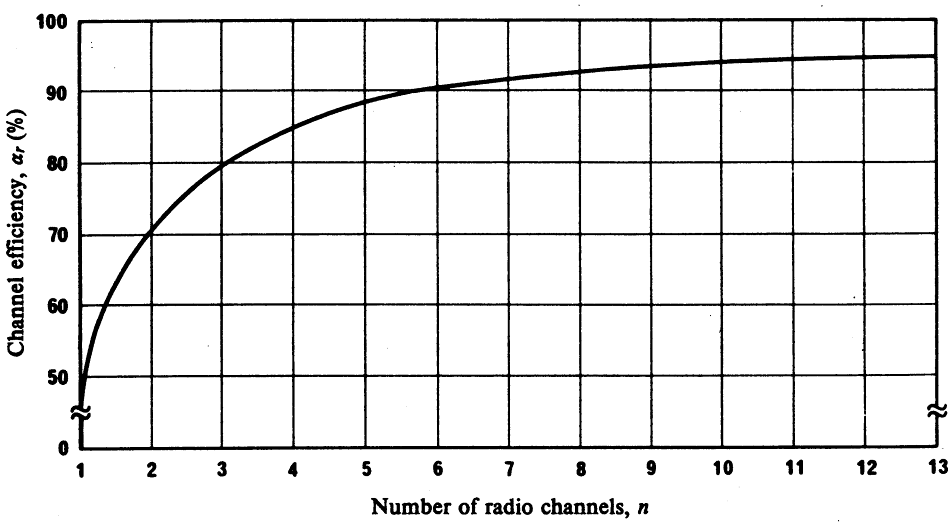

FIGURE 2 – *Radio channel efficiency in a trunked system*
(for a_m = 10, α_m = 0.005 E and P_r = 0.285)

α_m: traffic per MS
a_m: number of MSs per CP
P_r: probability of excess delay (delay equal to the mean holding time) under normal traffic conditions

However, with an increasing number of radio channels, the system becomes more sensitive to overload due to the increased traffic load per channel. Fig. 3 shows the permissible overload as a function of the probability of excess delay for different numbers of channels. From the overload criterion given in § 3.3, it may be concluded that the maximum number of radio channels in the case considered here amounts to 4 or 5, the overload criterion being slightly exceeded for $n = 5$.

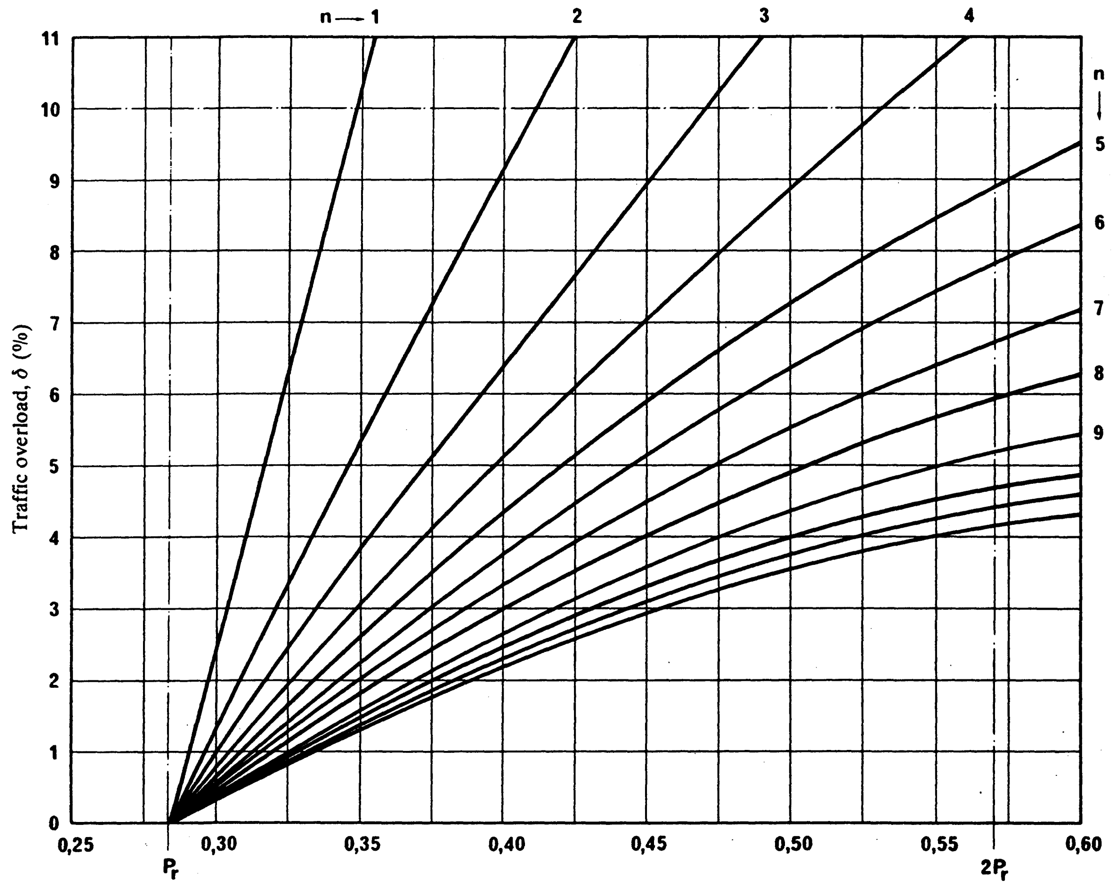

FIGURE 3 – *Traffic overload characteristics in a trunked system*
(for $a_m = 10$, $\alpha_m = 0.005$ E and $P_r = 0.285$)

n : number of radio channels
α_m: traffic per MS
a_m: number of MSs per CP
P_r : probability of excess delay (delay equal to the mean holding time) under normal traffic conditions

3.6 *Discussion of the results*

Assuming five radio channels and 10 MSs per CP, each MS producing 0.005 E, it follows from the formula in § 3.5 that the system is capable of handling 88 CPs and 880 MSs with a radio channel efficiency (see Fig. 2) of 88%.

One single-channel system with 10 CPs employing automatic sharing and serving the same number of MSs per CP with the same amount of traffic per MS, is capable of handling 100 MSs with the same grade of service, but with a channel efficiency of only 50%. The effective gain in spectrum utilization obtained by trunking thus amounts to 100(88 − 50)/50 = 76%.

When the system is compared with a manual system using a single radio channel and providing a similar grade of service, the effective gain only can be estimated; it will be of the order of 100%.

Figure 3 shows that if a smaller value of the permissible traffic overload and/or a larger value of the probability of excess delay under overload conditions is chosen, it is possible to increase the number of channels and, consequently, have a better spectrum utilization.

A further improvement is possible if, in contrast to what has been assumed in the present calculations, only those users are selected to participate in a particular trunked system, whose busy periods are not all coinciding.

It should be noted that the gain in spectrum utilization also depends on the inputs for the traffic data and further assumptions made, such as those mentioned in § 4 to 6.

4. Measured data on performance of trunked systems

In an effort to evaluate the performance of trunked systems, the Department of Communications, Canada, collected monitoring data for a ten-channel trunked radio system, with a single dedicated signalling channel, operating in the 800 MHz band and 12 conventional (non-trunked) channels operating in the 400 MHz band. For this trunked system, channels are occupied for the duration of a transmission only, while for the conventional systems the channel is occupied for the duration of the message.

Based on the average peak-hour traffic conditions, transmission occupancy and average probability of waiting were compared and are given in Table I.

TABLE I

	Average probability of waiting (%)	Average peak hour transmission occupancy (%)
Trunked system	13	64
Conventional system	53	33

Table I shows that the use of trunking resulted in considerable reduction in the waiting time and increase in the channel loading compared with conventional systems with similar types of user.

5. Unbalanced systems

As discussed in § 2.1, fleet operation means that the number of users on a mobile radio system will often be small although the number of mobiles may be large. Also, the load offered by different users will often vary considerably [Davis and Mitchell, 1979]. A system in which large and small users are mixed is termed "unbalanced" and in such a system the large users can receive a much better grade of service than the small users [Davis and Mitchell, 1978], a large user offers a large amount of traffic in comparison to a small user. This leads to the problem of whose grade of service should be used to determined the permissible loading of the system.

As an example, consideration is given to the channel efficiency which is possible in an unbalanced system, when a given grade of service criterion is applied to:

- the calls of the largest users only and,
- the calls of the smallest users only.

The grade of service criterion chosen for this example is that approximately 15% of calls may suffer a wait of more than one mean holding time. Only the time spent waiting for a channel is considered: the fleet delay is ignored.

The results for 1, 3 and 5 channel systems are shown in Fig. 4 [Davis and Mitchell, 1979]. When the grade of service criterion is applied only to the largest users then the channel efficiency can be significantly greater than it would be in a balanced but otherwise similar system. This is illustrated by curve A in Fig. 4. The probability of delay for the small users will then be worse than the specified grade of service criterion, but because they offer fewer calls the number of times they actually suffer a significant delay will still be small and perhaps acceptable. Curve A shows that unbalance reduces the amount there is to be gained from trunking in this situation because it allows the loading of a single channel to be increased.

If the grade of service criterion is applied to the small users in an unbalanced system the channel efficiency will, in general, be similar to the balanced situation as shown by curve B.

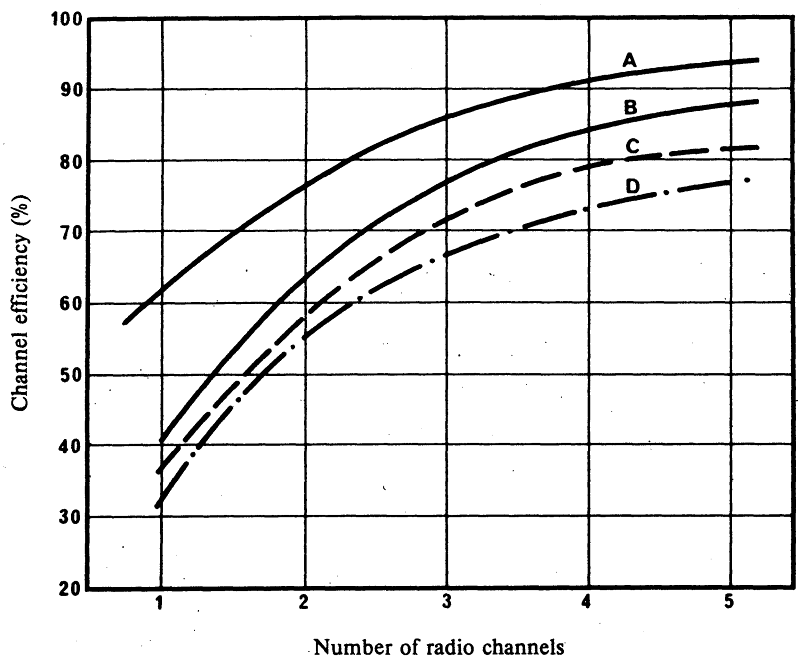

FIGURE 4 – *Radio channel efficiency in balanced and unbalanced systems as a function of the number of channels (such that the cumulative probability of delay greater than the mean holding time equals: 0.165)*

Curves A: results when the grade of service criterion is applied only to the large users (CPs) in an unbalanced system

B: results when the grade of service criterion is applied only to the small users in an unbalanced system

C: is for a balanced system in which all users offer the same amount of traffic

D: results from conventional telephone traffic theory

Note. – It is assumed that in the unbalanced case there are 1 large and 11 small equal users/channel (traffic ratio approximately: 11:1). In the balanced case there are 12 users/channel.

6. Signalling

In trunked systems with queueing of incoming call requests the signalling system used for handling these calls is crucial to the efficient operation of the system. The main design considerations are:

- the method for allocating the signalling channel;
- the method of access to the signalling channel;
- the method of contention control;
- the channel allocation time.

6.1 *Method for allocating the signalling channel*

The radio channel used for gaining access to the switching centre may be dedicated solely to signalling, but it is also possible to use any channel for that purpose. If, in this last case, one of the speech channels is temporarily idle, it may be marked as the signalling channel and be used as such during a limited period of time. In that case, the mobile attempting to place a call must detect this channel, for example by scanning the radio channels.

In both cases, dedicated signalling channel and non-dedicated signalling channel systems, the mobiles placing a call must all use the same channel and this may give rise to the problem of contention, that is, the problem of giving each contender a fair chance of gaining access to the channel in accordance with an established rule.

6.2 *Methods of access to the signalling channel*

There are two basic methods of accommodating in time the calls in the available signalling channel:

- an ordered method of access, for example a "polling" system in which each mobile is assigned a particular time slot which enables him to signal if he has a message to send,
- the random access method, for example some form of "ALOHA" [Kleinrock, 1976], in which the mobiles receive a standard starting signal inviting them to signal if they want to do so.

With polling, the signalling load depends on the number of users who have to be polled, rather than on the traffic offered. This is less efficient when there is a large number of users, each of whom offers traffic only occasionally. Moreover, any change in the number of mobiles requires some rearrangement of the polling routine.

The ALOHA type of systems may be much more efficient, provided the probability of "clashing", i.e. corruption of simultaneously transmitted calls, is sufficiently small.

6.3 *Contention control*

With the ALOHA type of systems every signalling message contains bits which are used for error detection allowing the control equipment to determine whether the message was corrupted by clashing with a simultaneous transmission from another MS. If the signal is successful an acknowledgement is sent; if it is not, the MSs concerned repeat their messages but with a randomly chosen delay between the first and second attempts. The process continues until the messages get through or a predetermined time elapses.

However, depending on the intensity of signalling messages and the availability of a signalling channel, there is a possibility of the system becoming unstable, i.e. the number of call requests pending (which are subsequently repeated and add to the new requests) becomes so large that the signalling channel's throughput is finally reduced to zero so that traffic handling ceases completely [Kleinrock and Lam, 1975].

Annex I to Part A reviews some alternative ALOHA systems and methods for contention control to improve stability.

6.4 *Channel allocation time*

For efficient operation the channel allocation time, i.e. the time that elapses between a channel becoming free and its being re-allocated, must be short compared with the average time between channels becoming free.

The channel allocation time depends on the signalling bit rate, the signalling format, the method of access and the system of contention control.

7. **Other important design considerations**

7.1 *Off-air call set up*

In order to minimize the amount of "air-time" wasted while a call is being set up, all calls should be set up "off-air" as much as possible. This will be particularly important where the call is being made through the public telephone network where set-up times may be appreciable compared with typical holding times.

7.2 *End of conversation message*

A reliable end of conversation message should be used so that channels can be made available again as soon as the previous call is completed. Additionally, some form of time supervision of the channel may be required.

8. Conclusions

Although trunking cannot solve all the problems relating to the frequency scarcity in the land mobile service, nevertheless it seems to be a valuable tool for frequency utilization.

As the improvement in channel utilization is very dependent upon the number of users, the way traffic is shared among them and the grade of service required, the improvement in channel utilization can be expected to vary considerably from one system to another.

Taking such limitations into consideration, it should be noted that improved spectrum efficiency and/or grade of service is obtained by trunked systems, regardless of type of modulation, channel bandwidth and the like.

However, in order to convert to a trunked system, the user has to incur additional cost due to a multi-channel radio set with more sophisticated signalling circuitry, and more complex base station operation.

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ANNEX I TO PART A

METHODS OF CONTENTION CONTROL

1. Introduction

This Annex reviews some alternative ALOHA systems and methods of contention control to improve stability, distinguishing between systems with and without feed-back.

2. Systems without feed-back

Carrier sense systems [Kleinrock and Tobagi, 1975] seem to be less suitable as they cannot be used for two-frequency simplex operation and also labour under the so-called hidden terminal problem [Tobagi and Kleinrock, 1975].

By employing "slotted ALOHA", in which the signalling packets are transmitted in successive time slots, the clashing probability is reduced by a factor of about two compared with the conventional ALOHA-system without time slots [Abrahamson, 1977].

Introduction of an additional frame structure such that a mobile may signal in one of the slots of a frame, only if it had the signalling packet ready at the beginning of the frame ("framed slotted ALOHA" [Okada *et al.*, 1977]), leads to a better throughput of the signalling channel than "slotted ALOHA" [Capetanakis, 1979; Schoute, 1980].

In both cases, stability is improved if capturing occurs, for example with FM-transmissions where a strong call request signal may be received correctly even though it occupies the same time slot as the weaker signals.

Although under normal traffic conditions "framed slotted ALOHA" employing, for example, 3 frames of constant length with 4 slots each, is unlikely to become unstable when capturing occurs, some form of dynamic (or feed-back) control may be desirable for the reasons set out in § 3 below.

3. Systems with dynamic (feed-back) control

Among the reasons justifying dynamic control, the following may be mentioned:

3.1 It is generally assumed that the number of new call requests arriving is a random variable following a Poisson distribution. This would be correct if the arrival process is a Poisson process *and* the time between signalling periods is constant. If, as is normally the case, the time between signalling periods is not constant, the assumption is no longer valid. The non-Poisson distribution results in an increased probability of the system becoming unstable, particularly under conditions of increased signalling intensity, such as those mentioned in § 3.2 and 3.3 below.

3.2 An additional burden is placed on the signalling system if some event takes place (e.g. an accident, traffic queue and the like) near the boundary of the radio zone. In this case, an increased amount of weak call requests may be expected during a prolonged time, resulting in a reduced probability of capturing.

3.3 Initial bursts of call request may occur if for some reason (e.g. technical malfunctioning of the system or excessive holding times of a temporary nature) there is no possibility to signal during several minutes in systems with a non-dedicated signalling channel, and mobiles are eager to transmit a request packet.

Dynamic control procedures have been studied by various authors [Lam and Kleinrock, 1975; Fayolle *et al.*, 1977]; a quantitive analysis of instability when there is no feed-back in the case of "framed slotted ALOHA" may be found in [Schoute, 1980].

An example of dynamic control of random access, especially for use in the maritime mobile satellite service, is the binary search procedure, described in Annexes I and II of Report 596, which, when used in conjunction with "framed slotted ALOHA", can give relatively high throughput [Capetanakis, 1979].

Another example, specifically adapted to private land mobile radio, is slotted ALOHA with dynamic frame length control [Schoute, 1980].

With this system the number of slots in a frame is not constant, but is automatically adapted to the expected demand, thus eliminating the cause of instability. The algorithm used in the system is handled by the switching centre and controls the number of available time slots in a frame on account of observations made on the utilisation of the time slots in a previous frame. Each time an ALOHA start signal is transmitted, the mobiles are informed about the available number of slots. Each mobile with a request pending then selects at random one of those slots.

The process of updating the number of slots in the new frame is based on:

- the number of successful, garbled and empty slots in the previous frame;
- the expected number of new calls since the beginning of that frame;
- some data which are computed off-line from stored information concerning the properties of the modulation system, the regional radio propagation conditions and the geographical distribution of mobiles.

Updating of the stored information to cope with gradually changing conditions is possible by means of an automatic learning process based on long term observations, according to appropriate software to be incorporated in the switching centre.

Under certain practical assumptions the number of time slots in a frame is equal to one for low traffic intensities and may increase up to, for example, 15 during the busy hour.

The variable number of time slots also results in a signalling time and a waiting time, which, for low traffic intensities, are both equal to about half of that required for the slotted ALOHA system with fixed frame length mentioned in § 2 above.

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PART B

SYSTEMS BEING INSTALLED OR PLANNED IN THE NEAR FUTURE

The systems referred to in Part B do not necessarily meet all design indications mentioned in Part A.

The basic specifications for the systems described are shown in Table I.

1. Example of a trunked mobile radio dispatch system in the United States

In the United States, trunked mobile radio systems are being installed for dispatch traffic using between 5 and 20 channels in the 900 MHz band. One channel on each system is a dedicated signalling channel where all requests for service and instructions to mobile stations users are made. The other channels are for two-way voice communication.

The dedicated signalling channel is organized in a time slotted configuration for contention control and uses a 78 bit word format requiring approximately 23 ms to be transmitted. A 21 bit word format at a 150 baud rate on the voice channel provides subaudible connect and disconnect signalling to mobiles. Error detecting and code correcting techniques are used to protect the integrity of information.

Requests for service are queued and mobile stations are served on a first-come first-served basis. Generally users speak for periods of only 2 to 3 seconds, with pauses of a few seconds in between. The system signalling speed allows the processor to recognize these pauses in conversation and reclaim the idle talk channel for reassignment to other groups. When the original user group is ready to continue its message, it will be assigned a new voice channel (or its request will be placed in a priority recent system user queue if no talk channels are available).

The use of this trunked system for extended area coverage, portable units and/or satellite receivers and direct mobile to mobile/portable communications is still being evaluated.