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CELLPAC: A Packet Radio Protocol Applied to the Cellular GSM Mobile Radio Network

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Abstract: The CELLPAC (CELLular PACket radio) protocol is introduced and its traffic performance is evaluated. The protocol is based on reservation of slots out of a GSM cellular radio network traffic channel, assigned to the respect. service and supports multi-packet message communication between mobiles of a GSM cell. Different from the usual way of operation a base station repeats packets received on the uplink of the CELLPAC channel on the resp. downlink, whereby a local area bus-like communication network is established. The protocol has been formally specified in Estelle and applied in a simulated mobile environment.

Keywords: Cellular radio, R-ALOHA, radio broadcast, road traffic informatics, emergency warning, short message service.

1. INTRODUCTION

1.1 General Remarks

Some hundred million vehicles are registered in Europe, of which some 30% permanently are circulating, causing accidents, high energy consumption and inacceptably high environmental pollution. One possible means known to reduce this drawbacks of traffic and improve the current situation, is to introduce the so-called intelligent road where traffic related data are collected by vehicles and environmental installations and exchanged between them [MO2000]. Many related systems will be based on data exchange via radio networks still under development at present.

Cellular radio is existent and is in use in many European countries to serve mobile telephone. Currently, such networks are mainly in use for point-to-point telephone conversation and - to a very limited degree - for data exchange between one mobile and another terminal at (in most cases) a fixed location.

During 1991, the first digital cellular mobile radio network will become operational in some European countries, which differs from its predecessors by following a commonly agreed standard set of services, protocols, and interfaces (I/F). The system was specified by Groupe Spécial Mobile (GSM) of CEPT to operate in the 900MHz band, assigned by the WARC (world administration radio conference) for operation of the system. The GSM-system is proposed in this paper to carry traffic related messages and an appropriate protocol to serve this purpose is introduced in this paper.

1.2 The GSM-SYSTEM ARCHITECTURE

The GSM-PLMN (Public Land Mobile radio Network), initially, will cover metropolitan areas and later on the total area to more than 90% [GSM88]. Interconnection to the public telecommunication networks (ISDN, data, packet) will be available.

Cells are used to cover areas with a maximum radius of 35km, but also microcells with radius down to 500m are foreseen to serve extremly high local communication demands. Each cell is controlled by a base station (BS), which provides radio coverage all over the cell. The radio subsystem comprises the mobile stations (MS), and BS systems, which are equipped with control, transmit, receive, and antenna equipment. A BS, typically, governs a number of 2 to 3 radio channels, (resulting in 16 or 24 traffic channels), which number mainly is limited through the total bandwidth available, and the cell cluster used. Size and coverage of a cell heavily depend on the geographical and morphological situation at a given location.

The switching subsystem comprises the mobile stations switching centers (MSC), which control a number of BSs and I/Fs to the various public voice and data networks, Fig. 1. A MSC is comparable in its functioning to an ISDN switch, but in addition performs functions to control and manage its assigned mobile radio system. Normally, one or more location areas (LA) are controlled by one MSC. A LA comprises a number of continguous cells.

Two types of registers serve to store and maintain the subscriber related data, namely the home location register (HLR), where static data and the current LA of the respective subscribers are stored, if their transceiver is switched on. The visitor location register (VLR) contains temporary data characterizing a subscriber, currently being outside his home LA.

Fig. 1 shows the four most important I/Fs between the system's components. U_m is the air I/F between MS and BS. This I/F is explained in more detail in Chap. 2.1.

The A-I/F between MSC and BS either uses a ISDN primary rate access (S_{2M})-I/F with a transmission rate of 64kbit/s per channel, or submultiplexing to provide 16kbit/s channels. The remaining two I/Fs appear between MSCs, and MSC and public networks, respectively. There, the S_{2M}-I/F is the preferred solution.

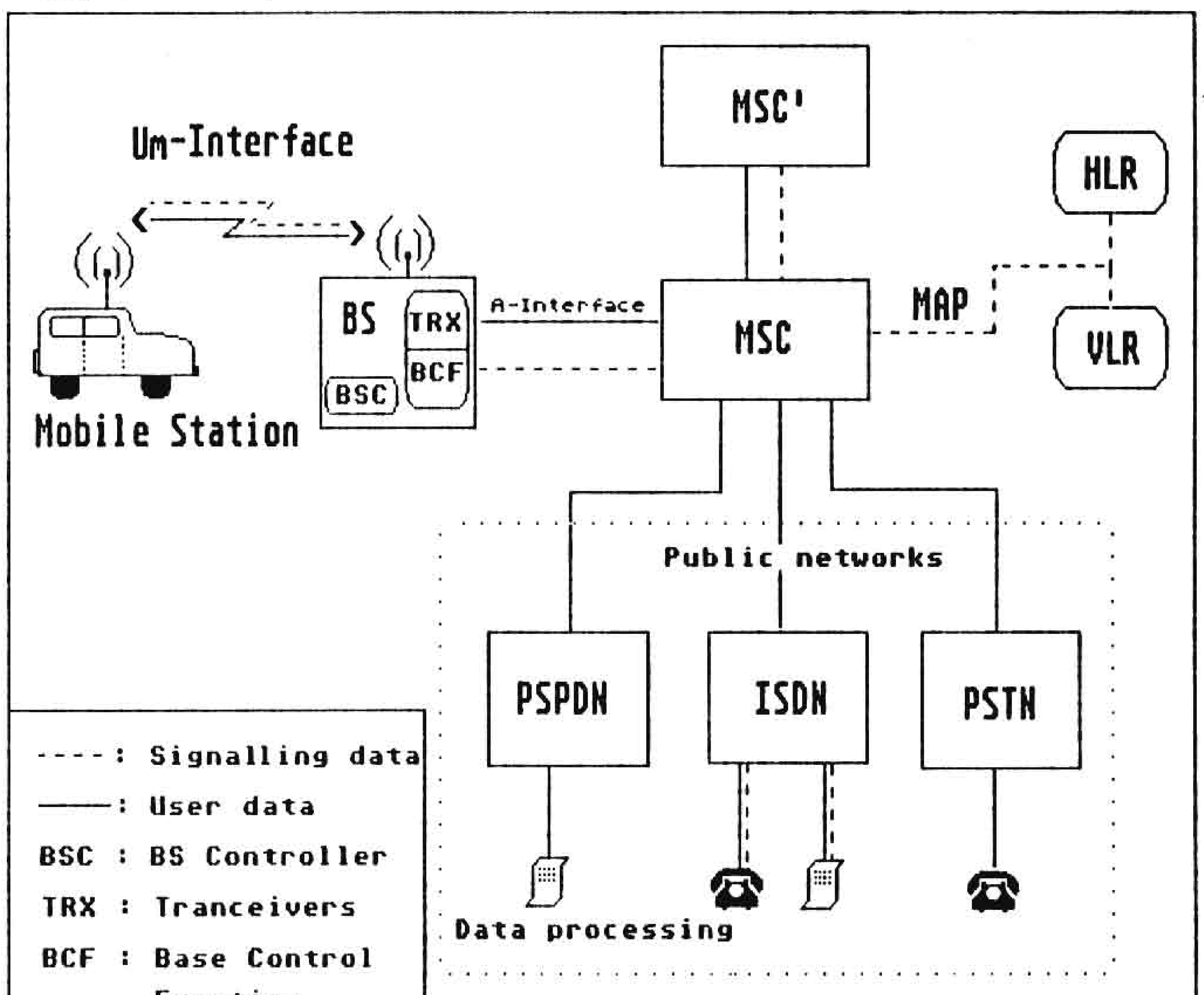


Fig. 1 Architecture and I/Fs

Before introducing the proposed protocol in Chap. 3, the radio part of the GSM-system is introduced, as far as needed. In Chap. 4 we present the simulated traffic performance results of the CELLPAC protocol. Possible protocol enhancements, two proposals to charge users of the CELLPAC service and a brief look at some possible applications conclude the paper.

2. Relevant Functions of the GSM-System

The U_m-I/F of the GSM radio part uses a combination of frequency and time division multiplexed channels, carrying a multitude of logical channels [GSM88].

2.1. Logical channels

Two categories of logical channels are in use, namely traffic channels (TCHs) and control channels (CCHs). TCHs carry speech or userdata, each coded in an appropriate way, offering a data rate of 22.8kbit/s. CCHs are used to carry signalling and synchronization data. Three types are to distinguish:

I. The **Broadcast Control Channel** is directed downlink from the BS to the MSs and comprises three logical channels:

a) Frequency Correction Channel (FCCH) to carry information to determine the frequency used by the BS and (optionally) the hopping sequence applied.

b) Synchronization Channel (SCH) to provide frame synchronization and frame numbering to MSs and to differentiate between the received BSs.

c) Broadcast Control Channel (BCCH) to carry global information related to the respective BS and its associated CCHS.

II. The **Common Control Channel** (CCCH) carries bidirectional signalling data between MSs and their BS, necessary for access of a MS to the system, e.g. to grant a TCH. It contains three logical channels:

a) Random Access Channel (RACH) as uplink part of the CCCH, used by mobiles to request a SDCCH channel from the BS.

b) Access Grant Channel (AGCH), used downlink by the BS to grant access to a SDCCH or to directly assign a TCH to a MS.

c) Paging Channel (PCH), used downlink to alert a MS.

III. The **Dedicated Control Channel (DCCH)** contains a set of control channels, used either in combination with other channels (CCCH or TCH) or stand-alone for point-to-point bidirectional communication between BS and a MS. The following logical channels are defined: The

a) Stand-alone Dedicated Control Channel, SDCCH, an autonomous channel, to support transmission of subscriber related data.

b) Slow Associated Control Channel, SACCH, which exists only in combination with a TCH or a SDCCH and is used to periodically transmit system related data. Besides other, the BS provides to the respective MS the time advance parameter to adjust frame alignment and the transmit power to the current needs. The MS uses that channel to transmit important measurements to the BS.

c) Fast Associated Control Channel, FACCH, only exists together with a TCH and is used for urgent signalling data, e.g. in conjunction with a handover.

2.2 Frequency- and Time-Division Channels

Two frequency bands are used by the GSM-system, namely in the range 890..915 MHz (uplink from MSs to the BS) and 935..960 MHz (downlink). In total, 124 pairs (uplink+downlink channels) are defined, each channel occupying a bandwidth of 200kHz. A frequency channel carries a periodic frame structure, divided into slots defining 8 synchronous TDM channels. Slots have a length of 0.577msec and a frame repeats in 4.615ms, Fig. 3.

Frames in frequency channels FD(n) are synchronized to each other. Slots within a frame are numbered from 0 to 7, and TDMA-frames are assigned numbers modulo FNMax=(26*51*2048)-1= 2715647, Fig. 2.

A complete cycle of TDMA-frames repeats in appr. 3.5h (called a hyperframe), and contains 2^{11}=2048 superframes. A superframe contains 1326 TDMA-frames and either comprises 51 26-TDMA-frame multiframes or 26 51-TDMA-frame multiframes. Multiframes with 26 TDMA-frames are used to carry TCHs and SACCHs. Multiframes with 51 frames carry BCCHs and SDCCHs, Fig. 3.

BS and MS transmit their data in bursts that fit into a 577 s-slot representing a channel in a frame. Voice and data are transmitted by a sequence of bursts in consecutive frames. A burst is 156bit, transmitted with a rate of 271kbit/s. Five types of bursts are to distinguish, Fig. 4 a) normal, b) frequency correction, c) synchronisation, d) dummy, e) access.

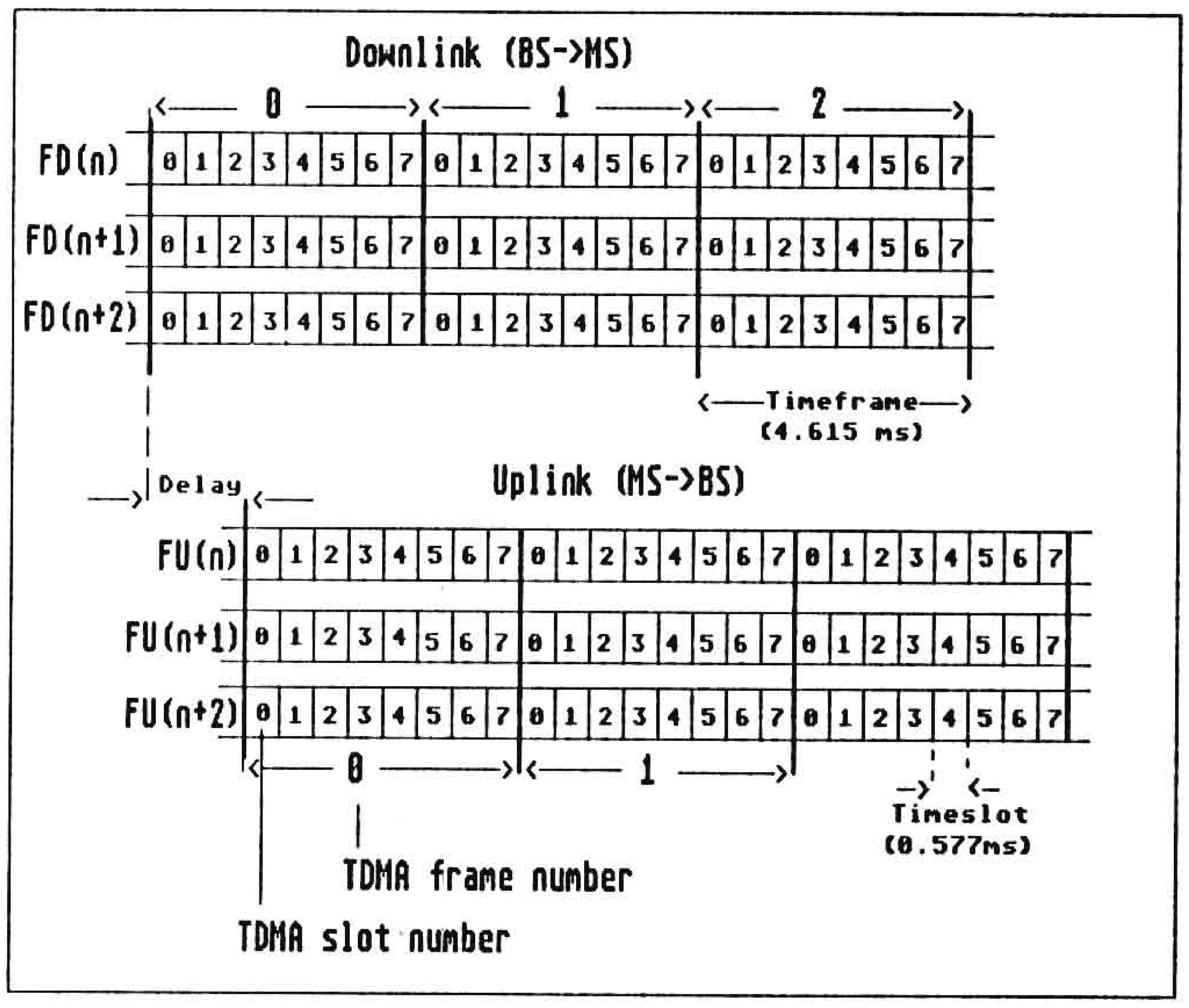


Fig. 2 Channel structure with GSM

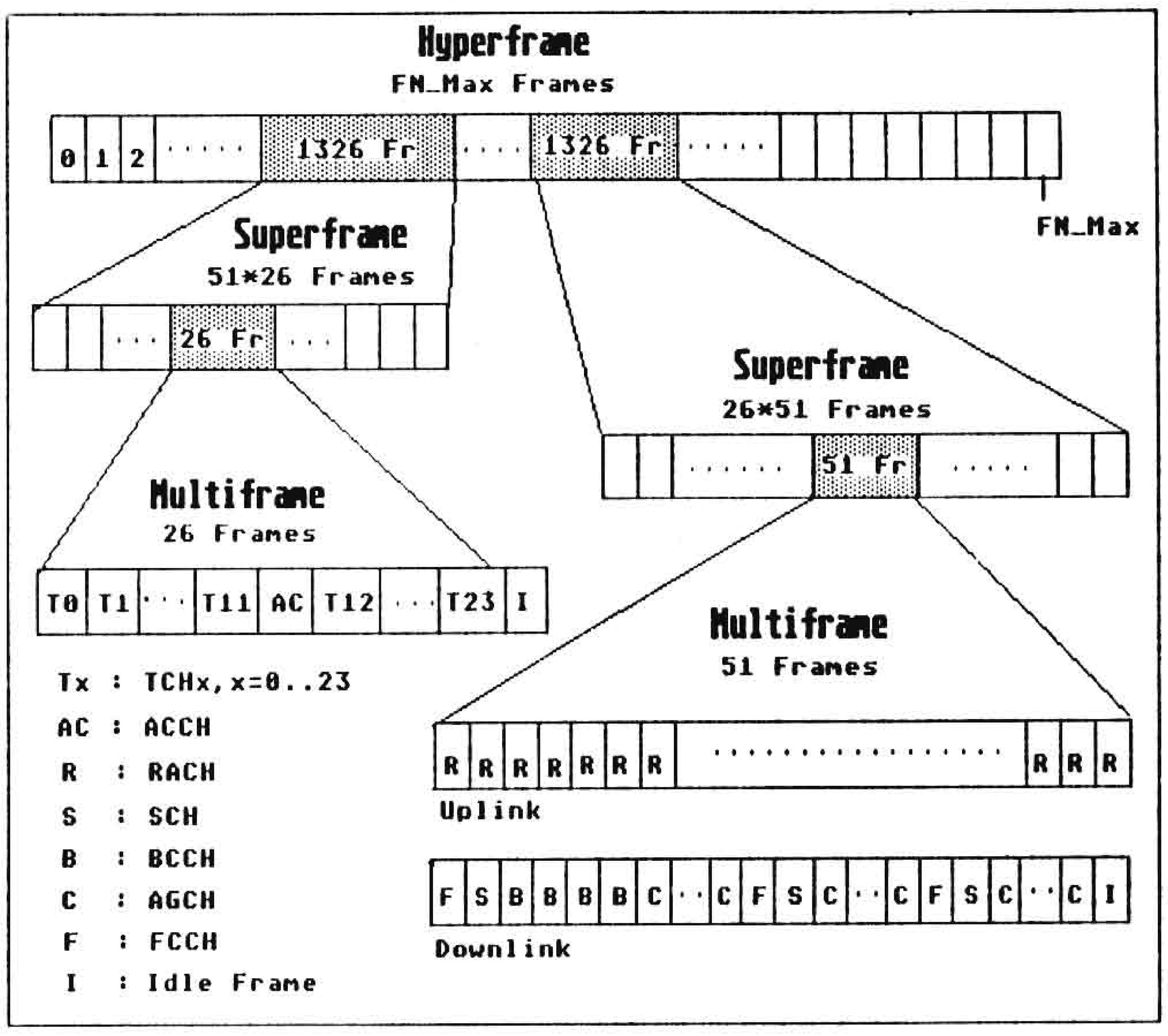


Fig. 3 Hyper-, super- und multiframes

The active duration of a normal burst is 148bit; a duration of 8.25bit is provided as guard time to avoid channel crosstalk. The pure message contains 112bit, the remaining Bits are used as control and tail bits and to carry the trainig sequence to support synchronization and adaptation of the receiver to the current radio channel parameters.

Frame 13 of a 26-TDMA-multiframe carries a SACCH-frame and frame 26 remains idle (if full-rate TCHs are used), Fig. 5. All other frames of such multiframe are used to transmit data bursts of MSs. Complete transmission of a multiframes requires 26*4.615ms=120msec. Since 24 out of 26 frames are used by TCHs, a multiframe carries 114bit/frame*24frames=2736bit user data resulting in a TCH's transmit rate of 22.8kbit/s.

The downlink slot used by the BS precedes 3slot the corresponding uplink slot, Fig. 2. Frame synchronization of a MS to the BS is performed by measuring of the round-trip propagation delay by the BS and transmission of an individual timing advance TA to the MS. Time alignment at a MS is performed by transmitting at time instants (3slot-TA) later on the uplink, than on the corresponding downlink slot.

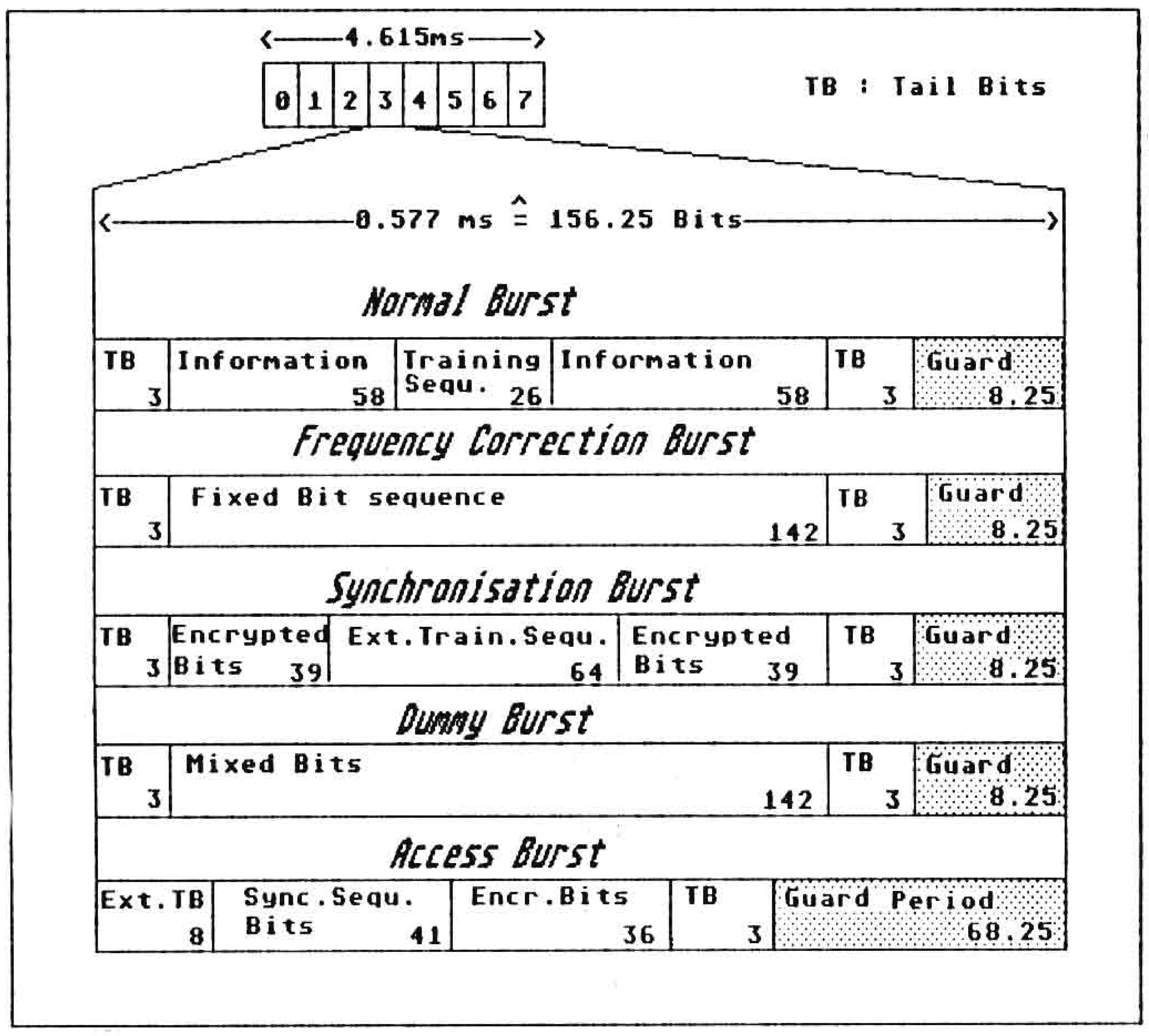


Fig. 4 Slot and burst formats

To establish a TCH, from observations on the BCCH the MS derives the position of the RACCH slot and transmits an access burst. Since the TA parameter is not available at the MS then, the access burst is much shorter than the normal burst and a substantial part of it is devoted to establish synchronization to the BS. The BS in turn determines the TA parameter and transmits an "immediate assign message" via the CCCH, thereby assigning a TCH to the MS. The TA parameter is actuated by the BS, whenever the slot synchronization exceeds one bit duration (3.6 s) and transmitted via the SACCH, as long as the TCH is in use. The maximum value of TA is 63bit, which corresponds to a maximum cell radius of 35km.

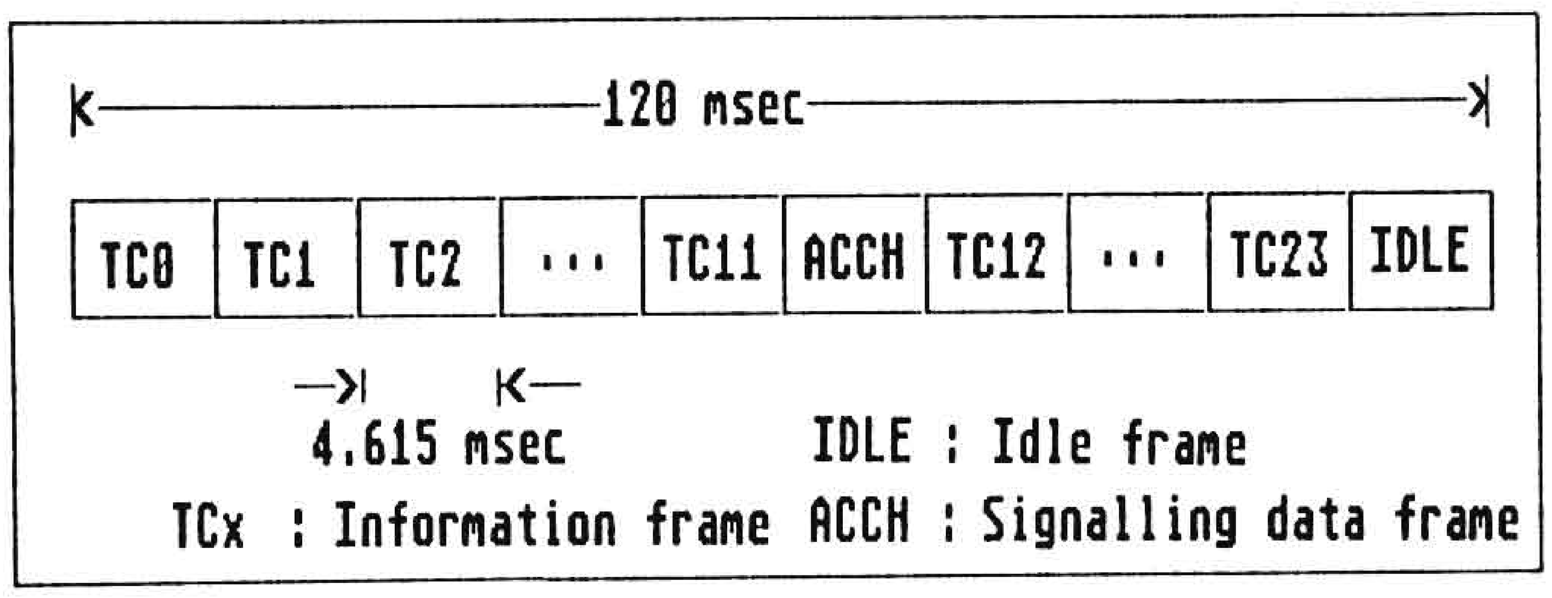


Fig. 5 TCH-multiframe structure

3. The CELLPAC Protocol

3.1 Main Idea

Motivation for proposing the CELLPAC protocol results from the idea that a service looks promising, where short- to medium-range communication between vehicles and with some infrastructure equipment is offered to enhance traffic security, reduce energy consumption and offer emergency call support on rural roads and highways.

The GSM-system is proposed to carry that service by reserving one or more TCHs per cell to establish a packet-radio network to transmit short messages originated from both, the MSs and the BS. Key assumptions are that

- the data traffic is bursty in nature,
- messages are relevant for many MSs in a cell at the same time,
- broadcast messages are to distribute by a BS, containing traffic status, route advices etc. originating from traffic control center.

MSs access the uplink of a CELLPAC TCH, they were assigned by the BS when entering the respective cell, via a random access protocol to transmit their data. The BS in turn repeats the data received on the corre-sponding downlink.

3.2 Contention Access and Reservation

Controlled access of MSs to the CELLPAC-TCH is not feasible, due to their large expected number and small transmit probability per frame. Therefore, access follows a modified R-ALOHA protocol [CRWO73], in that the first part of a message is transmitted via an access burst on the CELLPAC-TCH and subsequent parts are sent as normal bursts on the reserved channel. The access burst contains 36bit of user data, 8bit of which are useful for user information only [GSM 88]. Since a MS's message, normally, would contain more than 8bit, a sequence of normal bursts is used by a MS, each carrying 114bit of information.

A Final Bit (FB) contained in any bursts sent on the uplink provides contingency of bursts belonging to a MS's message. The FB set to 1 indicates to all receiving MSs that the next frame is free for random access; FB=0 says that the next frame is reserved for the current MS. The reservation mechanism supports transmission of a message in consecutive frames and minimizes system overhead, since the message header need not be repeated.

To support fairness, but allow sufficient flexibility, messages are variable in size but limited to some maximum number of bursts. A message carries source and destination address (BS, broadcast, etc.).

Fig. 6 shows a possible CELLPAC message format, called datagram. A source address might be a shortened identifier, uniquely derived by the BS or its MSC from the temporal mobile station identity, TMSI (see [GSM88]). A destination address might use the same length, e.g. 10bit.

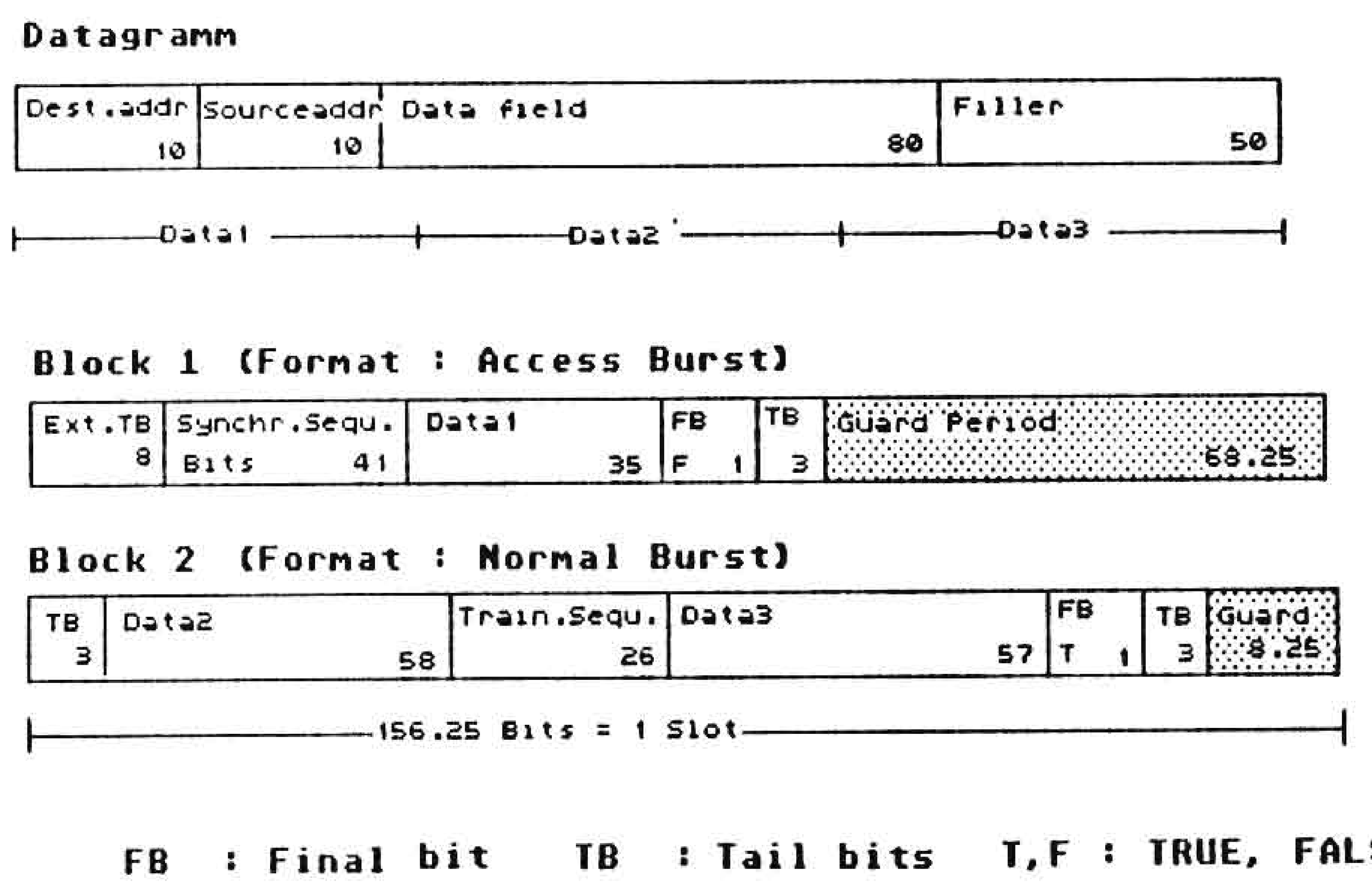


Fig. 6 A datagram, containing two bursts

The data field carries the information. Since a MS is able to follow its own transmission on the downlink, no bit interleaving (as used with the GSM radio link protocol, RLP) but a 3byte datagram check sequence might be used. A burst not completely used for information transfer, is filled with pad bits.

3.3 Synchronization and Power Control

The CELLPAC-TCH is shared by many MSs. This requires a modified procedure to provide MSs with individual frame alignment (TA) and power control (PC) parameters, to guarantee their proper functioning.

With CELLPAC the access burst is transmitted using the maximum transmit power allowed in the cell. This burst is complemented by the BS with the correct TA- and PC-parameters for that MS, and transformed into a normal burst to be transmitted on the downlink, Fig. 7a.

A MS, in turn aligns its frame, adapts its power and transmits normal bursts containing more data of the same message, until it is finished.

Since the length of a datagram is limited, no further frame alignment or PC appears necessary during transmission of a datagram.

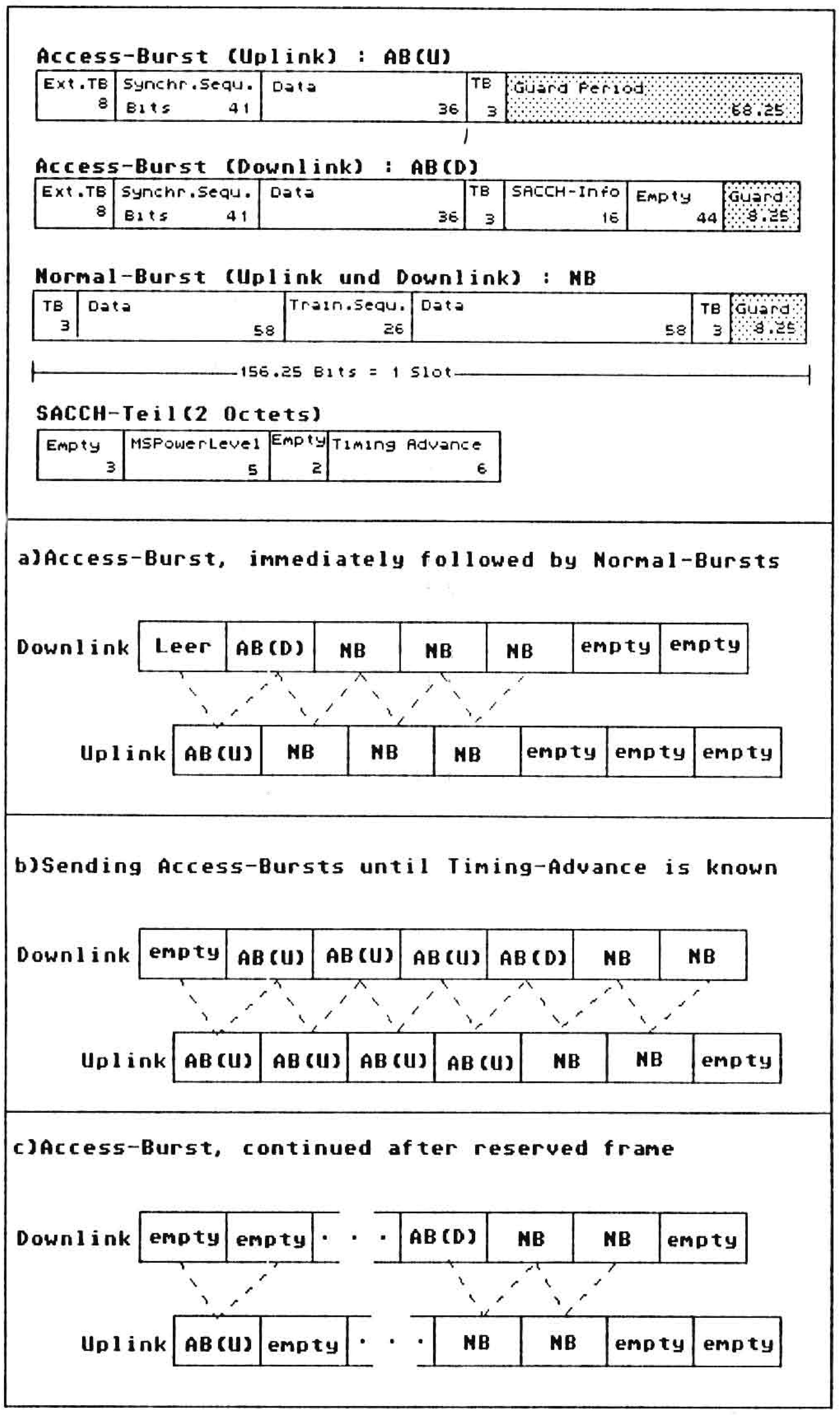


Fig. 7 Comms. cycle assuming delay in the BS

Use of the SACCH remains unchanged, as defined by GSM, to transmit information useful to all receiving MSs of the shared TCH, but the TA- and PC-parameters transmitted there are ignored. Instead of them, the SACCH might carry CELLPAC-specific data (e.g. number of participating MSs, uplink load etc.) transmitted by the BS.

It is known that a channel, accessed via the R-ALOHA protocol, can be loaded at maximum to a certain percentage, depending on the datagrams' lengths [LAM80]. Any uplink capacity not used is available to the BS on the downlink to control the receiving MSs in the respective cell and to distribute broadcast messages to them.

If the BS is unable to provide the TA-/PC-parameters in the repeated access burst (i.e. within 5 slots), alternatives a) or b) might be used:

a) Consecutive access bursts are used on the uplink, until these parameters are received, and normal bursts are used then (Fig. 7b).

b) After transmitting an access burst, MSs wait for reception of their repeated burst containing the desired parameters, before sending more data. This burst is placed by the BS to not collide with frames reserved by other MSs, (Fig. 7c).

3.4 Implicit ACKs, Collisions, Back-off and Overload Control

With the GSM-system a MS is assigned an individual cryptographic key when entering the BS. With CELLPAC, this procedure must be modified, since all MSs, following the same TCH, must use the same key. We propose to assign the key on a per cell or location area basis and change it once per day (necessary for charging purposes).

Access: A MS, ready to transmit, waits until a current transmission of some other MS has finished (FB = 1). In addition, slots 13 and 26 are not used, which carry the SACCH. Slots used by the BS do not delay access to the uplink, Fig. 8. Access and all following bursts are encrypted.

Acknowledgement: The MS receives an implicit acknowledgement, when its burst is repeated on the downlink. To better adopt the CELLPAC-protocol to the applications' needs, features not usual with the R-ALOHA protocol were introduced, like error correction, repeated transmission of bursts not correctly received by the BS, p-persistent access, delay limit, duplicate message control, congestion control:

Error Correction: If an error was detected by a MS in the repeated burst, it is retransmitted and the Discard Bit (not shown in Fig. 6) is set, indicating that the previous burst must be deleted at the receiving MSs.

Collision: The access burst is transmitted via the S-ALOHA protocol, which might result in a collision at the BS and no repeated burst on the downlink. Then, the MS follows the back-off algorithm specified below.

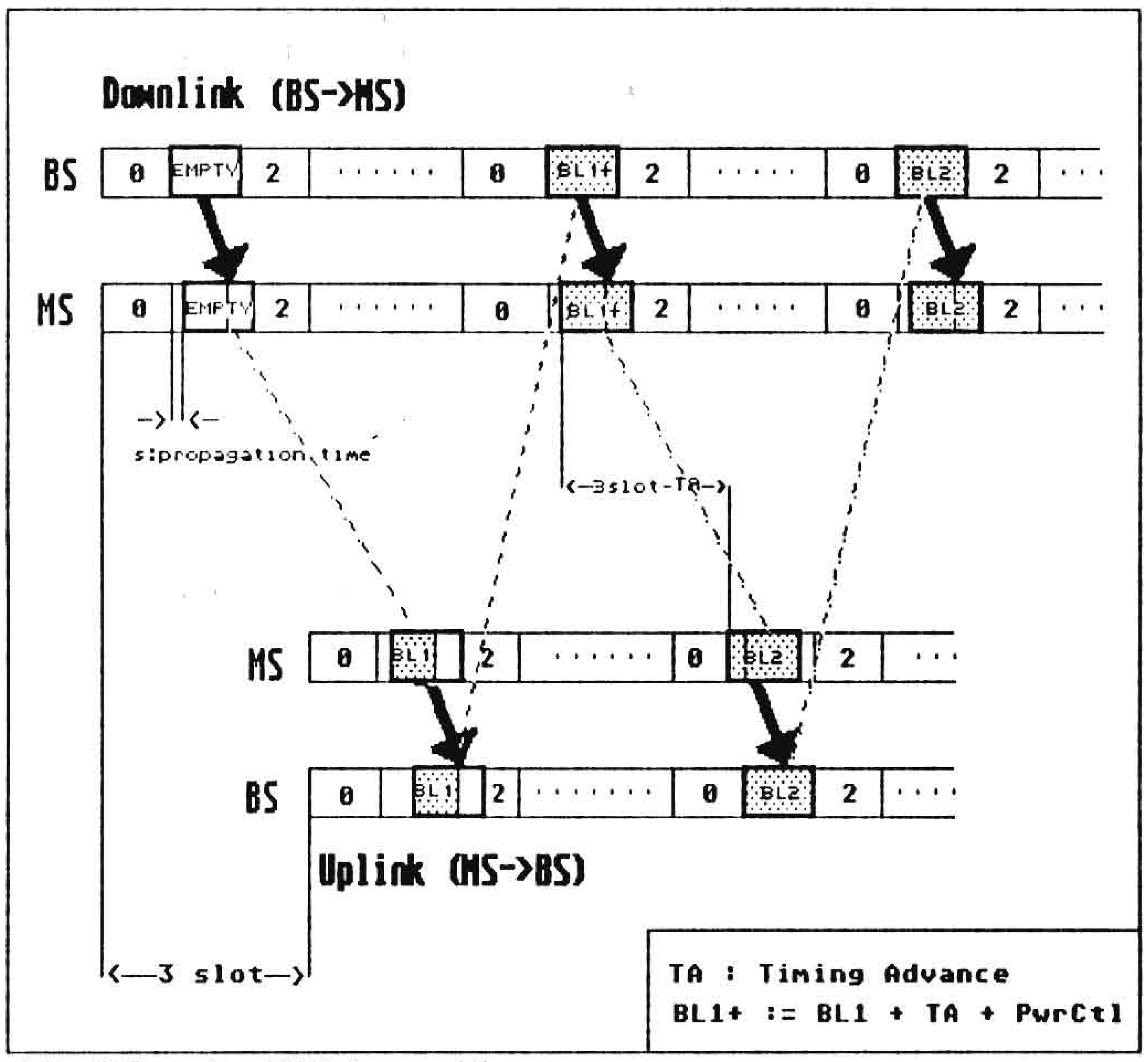


Fig. 8 Use of a TCH detected free

Receive Error at BS: If a normal burst was not repeated, the MS transmits it, which action is repeated twice, before transmission is canceled.

Back-off Algorithmus: If a ready MS detects the TCH reserved (FB = 0), it follows a p-persistent access protocol: When the TCH was detected free, it transmits with probability p in the next frame, and defers with (1-p). A back-off algorithm determines the length of the delay period, until the MS may try again. The algorithm is activated also, if an access burst is not repeated in time or a normal burst was repeated twice but was not successful. The back-off period is a random variable drawn from a linear distribution with mean 2^i frames (binary exponential back-off), where i is the number of transmit attempts of a MS for the same datagram.

Delay Limit: During a high traffic load to the CELLPAC-TCH, the delay at MSs (from first transmit attempt until success) might exceed some given margin, whereby the transmit data might loose actuality. A maximum delay is used and a datagram discarded, when this limit is reached. Instead of the delay, the number of collisions of a message might be used. This substantially contributes to the system stability.

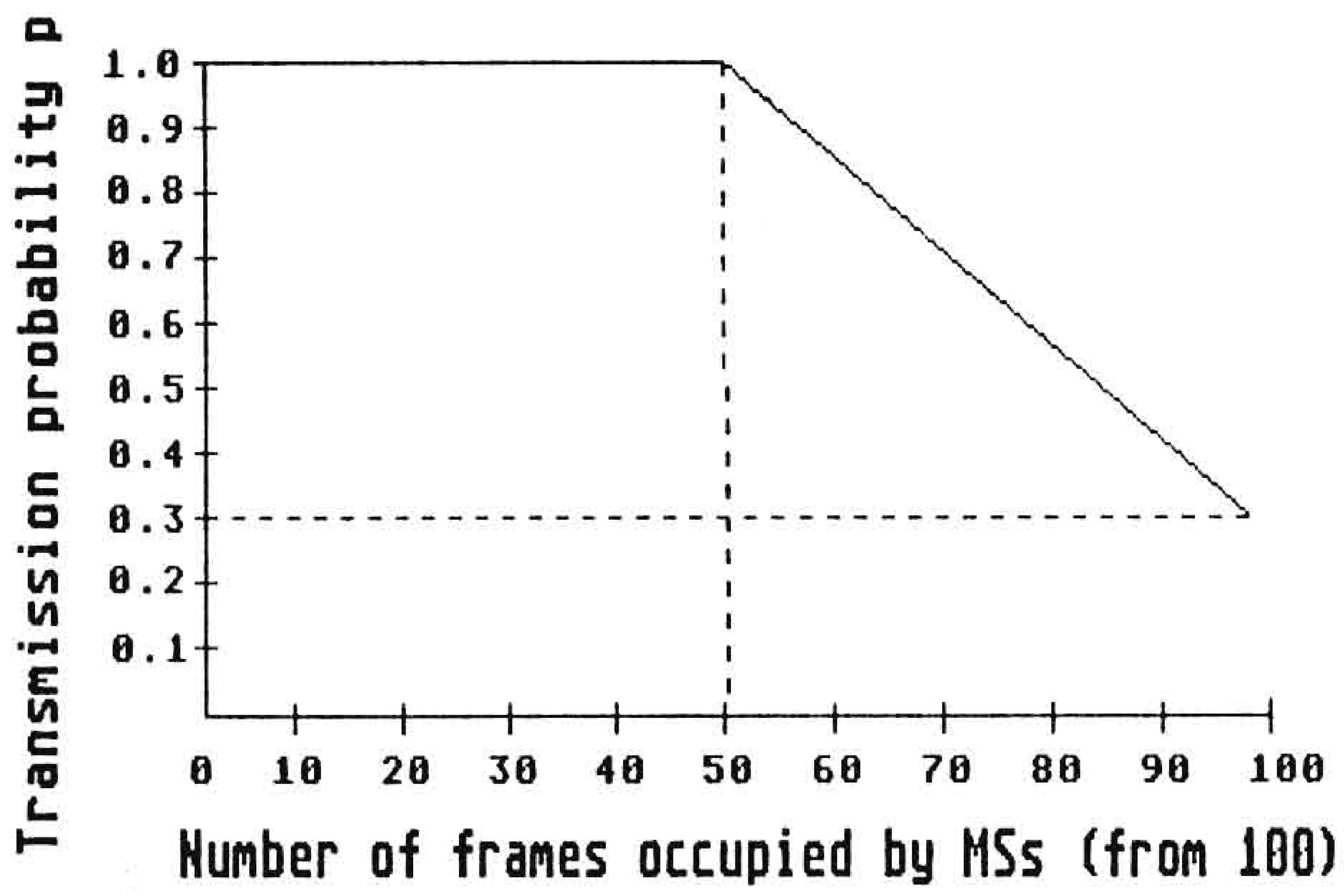


Fig.9 Persistence p over observed traffic

Duplicate Message Control: The applications considered might produce bursty traffic by many co-located MSs, if they've detected the same traffic or road-status related information (congestion, fog, icy road, etc.) at quasi the same time and try to distribute it. It is assumed that MS are equipped to recognize such situations and cancel their own transmission planned, if an information scheduled was already received from other MS repeatedly.

Congestion Control: The persistence value p used depends on the traffic load, observed during the last 100 frames before access, and is calculated, decentrally, by a MS by counting the percentage of successful frames used by MSs. P is reduced with increased load, resulting in a reduced traffic offered by MSs. Since p must be high with small and medium load, to not reduce channel capacity and access delay, but low under heavy load, we used the function, shown in Fig. 9. Assuming message lengths with mean 2 or 3 bursts, a load up to 0.5 is termed normal and p=1 is used then. Under higher load we use currently p = 1.0-(used_frames-50)*0.7/50.

Since a MS cannot switch on its transceiver and/or enter a cell and transmit during 100 frames (461ms), it always has available its own estimate of the current traffic load. Instead of estimating p decentrally, the BS might distribute the current value of p to be used.

4. Simulation Model of CELLPAC Protocol

The simple version of the protocol (Fig. 7a) was formally specified in Estelle and its functionality tested, using a compiler Estelle-to-C [CHAN87]. To analyze its traffic performance, the specification was used as a basis to develop a simulation program and figures under various load conditions were derived. Besides a very large number of MSs in a cell (modelled by a Poisson arrival process of messages), we also investigated performance for a limited number of 30 MSs.

Datagrams with fixed size of 1, 2 and 5 bursts and with negative exponent-ially distributed length (mean 10) were investigated. Throughput, mean delay, utilization of the uplink TCH and percentage of collided packets were determined as a function of the offered traffic G (burst/slot) and shown in Fig. 10 for a large number of MSs. Since we used a p-persistent S-ALOHA access protocol, our results are somewhat different from known analytic results [LAM80]. The tendency, however, is the same: Single bursts (like S-ALOHA packets) are served with the throughput over G performance known [KLEI76], Fig. 11. Since two out of 26 frames are reserved in a TCH, the max. throughput is limited to 0.35 instead of 0.38burst/slot, see pointed and dashed curves. Due to the p-mechanism, the result for 1burst/datagram differs from that of S-ALOHA, cf. dash-poited curve in Fig. 11 which is shown also in Fig. 10.

Throughput is increased with the length of datagrams. The collision probability is the higher, the shorter datagrams are. Delay appears to be quite small and is the greater, the longer datagrams are, which results from wait for a free frame. In addition, the persistence parameter p has an impact on delay, which is currently under investigation. Due to the overload control introduced, the protocol is very stable, even under heavy overload. A MS is allowed 6 transmit attempts at maximum.

5. Enhancements and Application Areas

5.1 Handover and Cell Boundaries

MSs in the GSM-system periodically (each 480ms) transmit the mean of measurement results characterizing their receive level, quality etc. for evaluation at the BS to decide, which cell is best suited for use. When another cell was decided to be used by the MSC, a handover is initiated.

Users of the CELLPAC-service might wish MSs at a cell boundary to be able to follow and use the TCHs of adjacent cells, which would require MSs to be equipped to concurrently operate the CELLPAC-TCHs of adjacent cells and enter the respective BS as soon as the related BCCH is received sufficiently well. The GSM-Rec. are violated then.

Operation of a single TCH guarantees access to the most relevant TCH, which deliberately can be selected by the MS, possibly in a slow TDMA mode of operation. One possible way to support MSs at cell boundaries via the CELLPAC-service would be, to establish a periodic broadcast service to repeat actual, but cell specific news by all BSs. All MSs are reached then, for which these news are of importance, even if they would have missed some message due to fading or interference conditions.

5.2 Charging

Charging of MSs for use of CELLPAC might depend on the applications subscribed to. Two alternatives are proposed for further discussion:

Monthly Rate: A fixed fee is charged in this model, similar to charging for broadcast radio services. A MS need be authorized, which status is reached after having subscribed to the service, e.g. by having paid a mothly charge or presented a smart card to the BS. Authorization is withdrawn by excluding the MS from access to the secret key currently in use, if its credit is exhausted.

Charging for usage: Fees are based on usage of the service by a MS, which is stored in the HLR and charged to the subscriber. As communicating MSs are located in the same cell, fees should depend only on the duration of usage of the service and not be distance dependent.

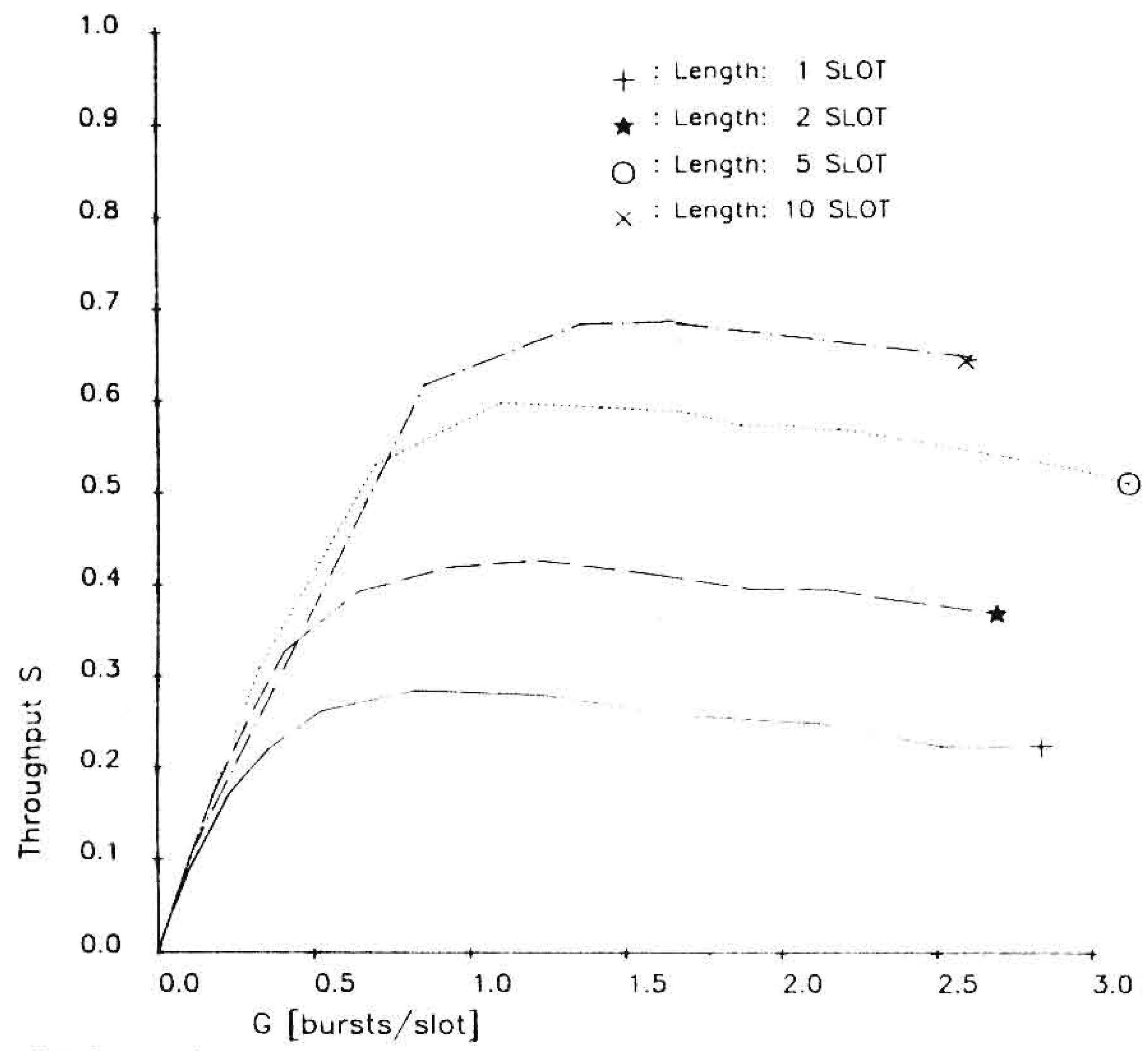
5.3 Application Areas for CELLPAC

The automotive and electronics industries currently investigate possibilities to enhance the efficiency and security of road traffic. Services are under discussion, which aim at supporting drivers in various ways.

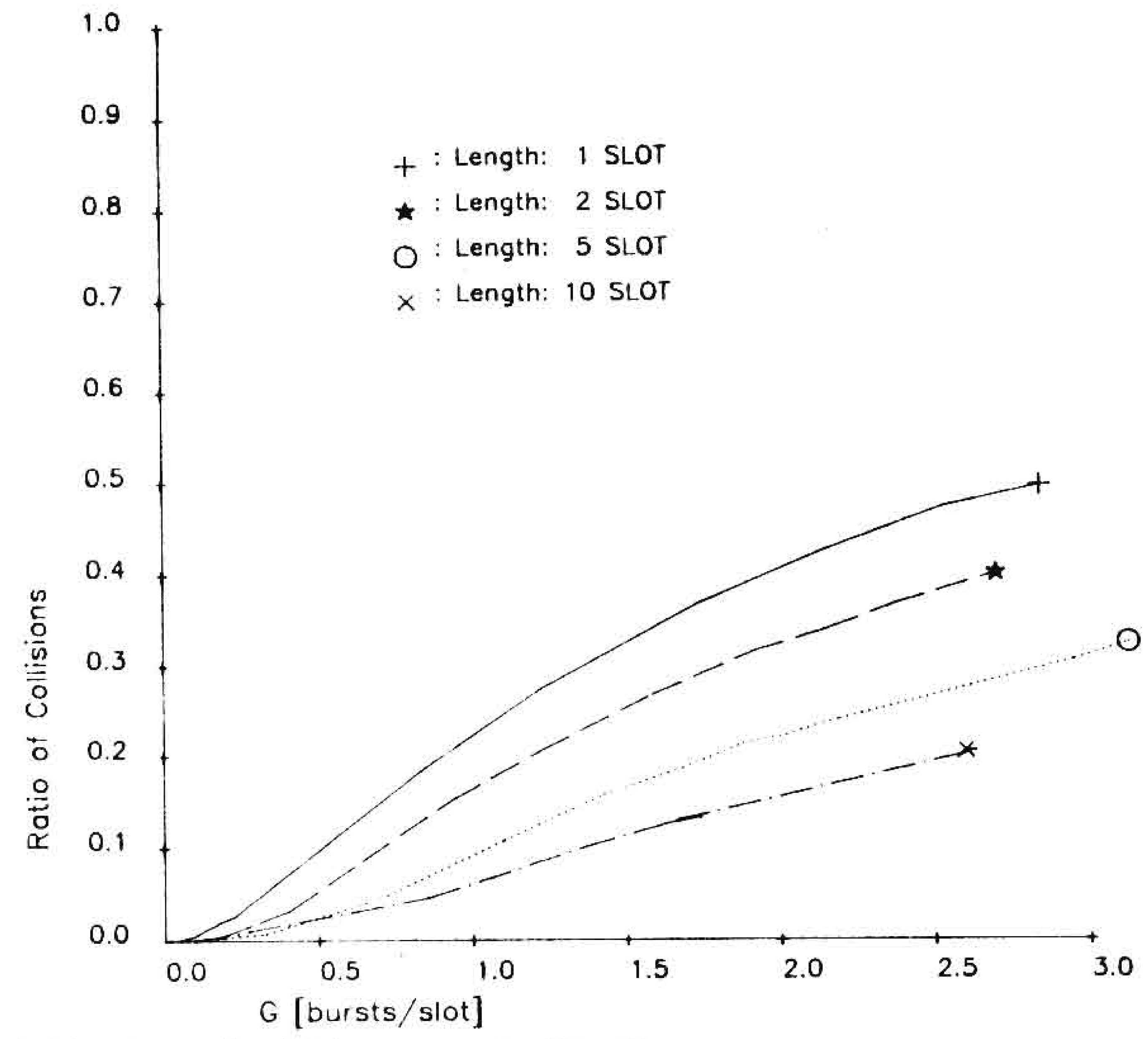
The CELLPAC-protocol, applied to the GSM-system, is one candidate to carry such services.

A service Emergency Signalling might be used to inform subsequent vehicles in $\leq$0.5s and, additionally, alert the nearest emergency control center via the BS. Such type of service is addressed in GSM-Rec. 02.03 (Emergency Call) where user's data are defined to be transmitted as speech in a point-to-point mode of communication between MS and emergency control center. One disadvantage is, that other vehicles, being in the zone of relevance to the respective MS, are unable to recognize the emergency situation, which is not the case with the CELLPAC-protocol. Another service possible with CELLPAC is traffic-situation dependent global route guidance to vehicles in a cell to reduce traffic jams. The local relevance of information distributed via the BS is much higher to the vehicles, than is possible today, where such information is directable only to much larger areas, namely the receive range of broadcast radio. One advantage is that inside a cell only those messages are broadcast that are relevant to the respective MSs. Traffic reports can be allocated to the related cells and become much more regional (depending on cell diameter) than today.

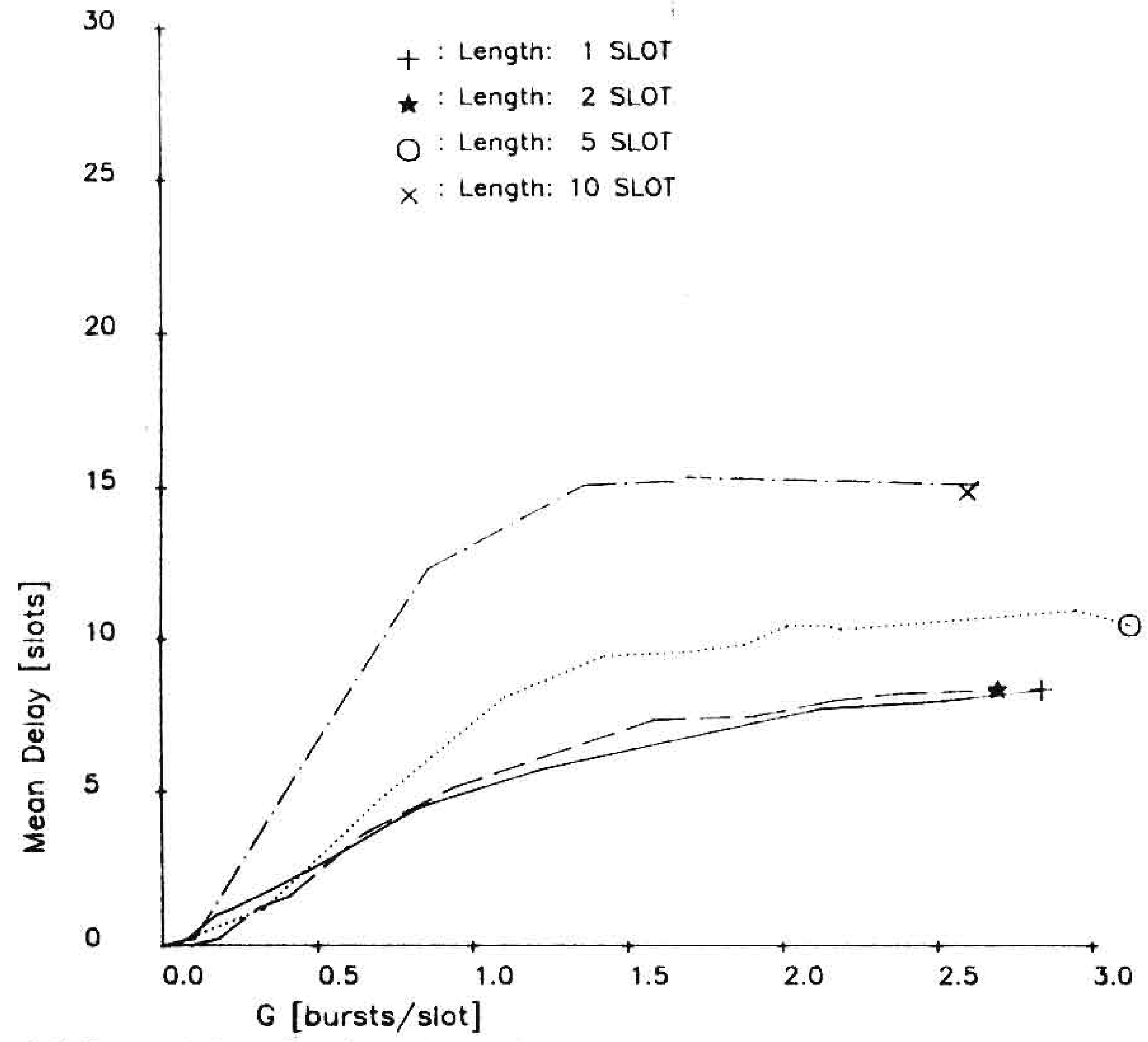
GSM-Rec. 02.03 defines the service (Short Message Cell Broadcast) which can better be served by CELLPAC. The service is based on pure broadcast of short messages (<75 char.) in a cell and can be efficiently carried by CELLPAC, since -besides others- an acknowledgement is possible and the MSs can also be sources of such messages.



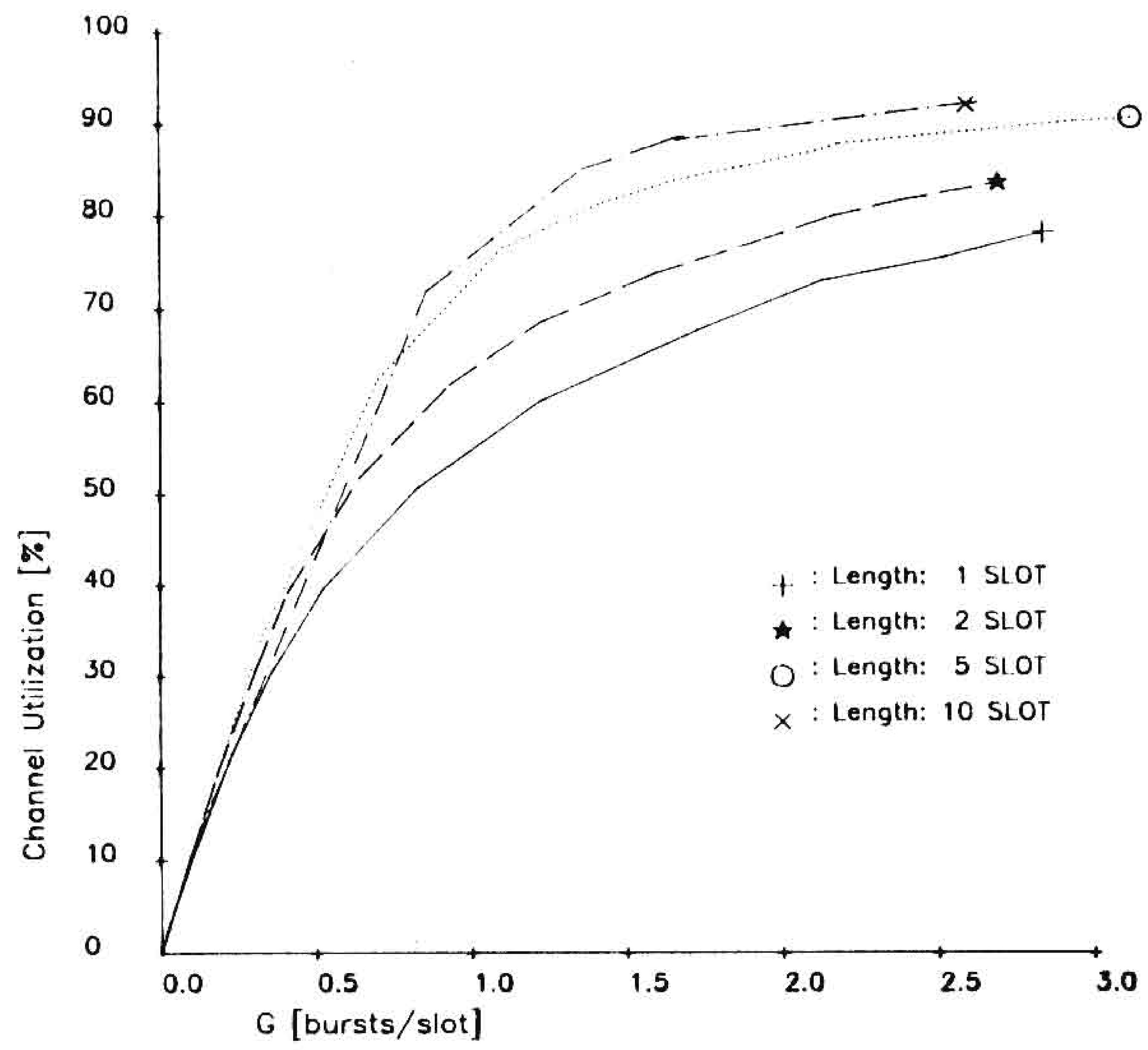
a) Throughput (pac/slot) over traffic G



c) Number of collisions over traffic G



o) Mean delay (in slots) over off. traffic



d) Utilization of uplink over traffic G

Fig. 10 Performance over offered traffic G (<7 transmit attempts)

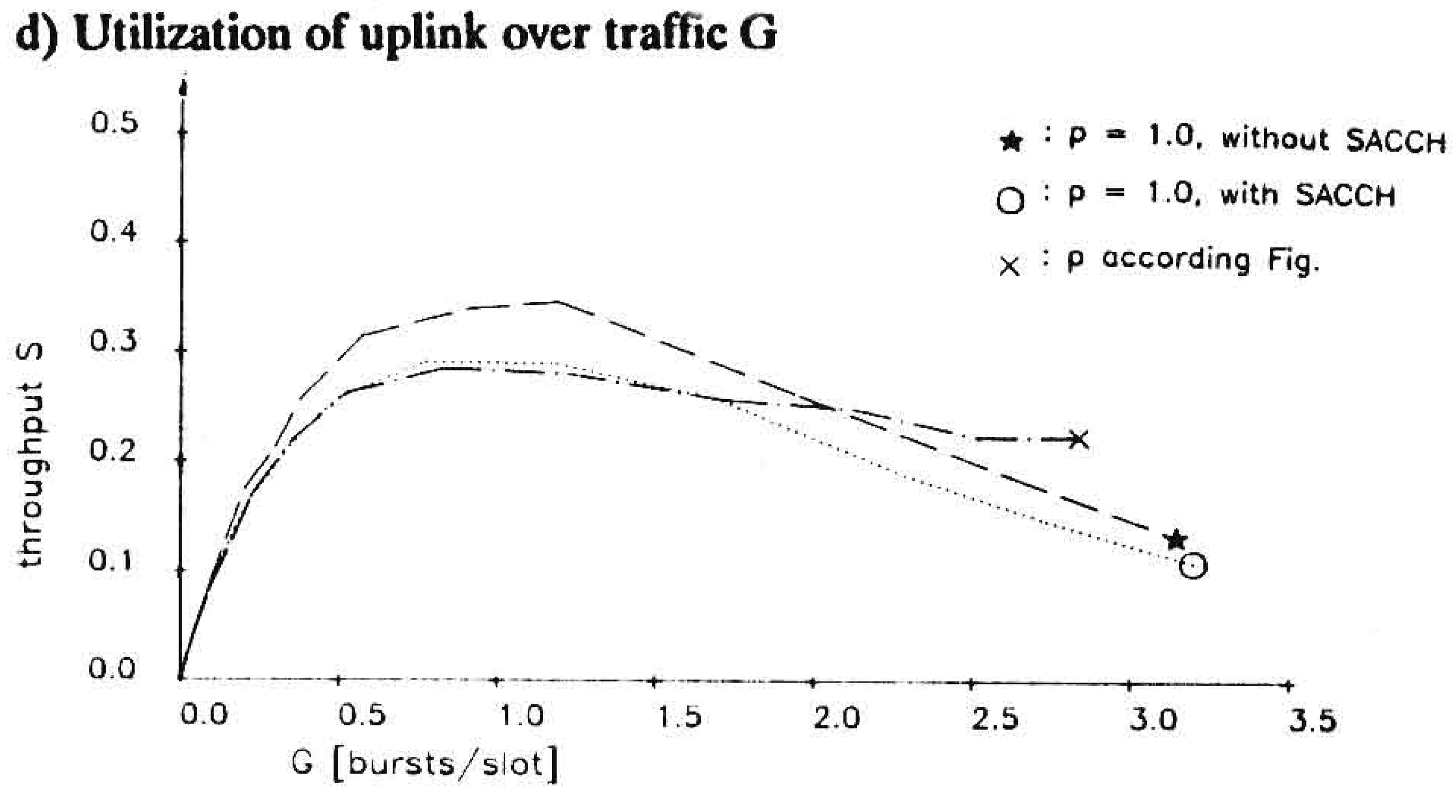


Fig. 11 Throughput over G for single packet datagrams and parameter p

Services to broadcast messages to MSs, originating from the fixed network, can be integrated, since the downlink TCH always has spare capacity, even under heavy load, thanks to bursts collided on the uplink.

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