ABSTRACT

For almost three years the European Telecommunications Standards Institute (ETSI) has been working on the specification of general packet radio service (GPRS) for the Global System for Mobile Communications (GSM). In the course of 1997 standardization will come to an end, and a first introduction of GPRS by a service provider or network operator is likely to take place in 1999. The new service will accommodate data connections with variable bit rates and high bandwidth efficiency, and thus offers the possibility to attract a wide range of new applications to GSM networks. In this article possible applications and elementary concepts and service characteristics of GPRS will be explained in detail. Furthermore, a medium access control protocol that conforms to the draft standard proposal for the GPRS air interface will be introduced and analyzed. Thereafter, the simulation model will be described and simulation results will be presented. The performance analysis carried out shows reasonable performance even under high load conditions.

Concepts, Services, and Protocols of the New GSM Phase 2+ General Packet Radio Service

Götz Brasche and Bernhard Walke, Aachen University of Technology

Up to now, the main application of most mobile radio systems, like the pan-European Global System for Mobile Communications (GSM) [1], has been mobile telephony. More recently, the use of data applications like facsimile transmission or short message exchange is becoming more popular.

The fact that the dissemination and acceptance of mobile radio systems is much better than expected characterizes the '90s, in which the requirement for human mobility is becoming more and more important. Thus, the demand for all-embracing mobile communication at any time and place is steadily increasing. Although even in the future mobile telephony will keep its dominant role in mobile communications, new markets are opening up.

Examples are wireless personal computers, mobile offices, and electronic funds transfer, as well as road transport telematics, field service businesses, fleet management, and remote telematics.

Seen from a technical viewpoint, applications that are connected to these markets are characterized by bursty traffic. In that case, packet-switched access mechanisms are known to give better utilization of the transmission medium than circuit-switched ones; the transmission medium is used on demand only and, with statistical multiplexing, one physical channel can be shared by many users.

Consequently, emerging and future digital mobile radio systems based on time-division multiple access (TDMA), such as the trans-European trunked radio system (TETRA), will apply a packet-switched approach rather than the circuit-switched one, as is currently used in GSM.

From the user's viewpoint packetized transmission within GSM will be more convenient not only because of the new services that could be provided. In contrast to time-oriented charging applied for circuit-switched connections, packet-switched data services will allow charging depending on the amount of data transmitted and the quality of service negotiated.

In order to satisfy the increasing user requirements and to preserve competitiveness, one major concern of GSM Phase 2+ development, led by the European Telecommunications Standards Institute (ETSI), has been to specify a general packet radio service (GPRS) that accommodates data connections with high bandwidth efficiency.

In this article, the key concepts of GPRS are explained, based on an interpretation of the working assumptions of the ongoing standardization within ETSI. First, general requirements imposed by the end users and network operators are studied, and an overview of the GPRS service characteristics is given. Then, the logical architecture and new GSM network components that are required to support packet switching are described before the functional models for routing and mobility management are introduced.

Thereafter, the data communication architecture for both signaling and data transmission is discussed. Emphasis is put on the GPRS air interface since performance of packet data services is strongly influenced by efficient use of the scarce radio resource. With the master-slave dynamic rate access (MSDRA) protocol, a medium access control (MAC) protocol is introduced that adheres to the draft GPRS air interface standard proposal [2]. The protocol is characterized by dynamic bandwidth allocation and multislot operation; that is, one mobile station may use more than one time slot of one or more channels dedicated to GPRS at a given time.

The remaining part of the article deals with the performance analysis of the protocol. First, the simulation assumptions are clarified and evaluation criteria like mean packet delay and throughput against channel utilization are defined. Then, the simulation environment that has been developed for performance analysis is described. The GPRS protocol simulation tool *GPRSim* is capable of modeling different input traffic as well as realistic radio channel behavior, and includes features for graphical representation of the protocol

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and channel states. Finally, the simulation results are discussed and conclusions are drawn.

General Packet Radio Service

The main intention of the specification of a GPRS has been to enlarge the limited range of existing GSM data services offering data rates up to 9.6 kb/s only. To enable support of new data applications with a convenient quality of service, the GPRS concept foresees bit rates of nearly 170 kb/s that can be flexibly allocated according to actual user demands.

Applications and Requirements for GPRS

The primary interest of end users of a new packet data service is that applications used to run within their fixed computer environment should be supported at moderate cost and without notable changes in operation. The user view of GPRS is illustrated in Fig. 1.

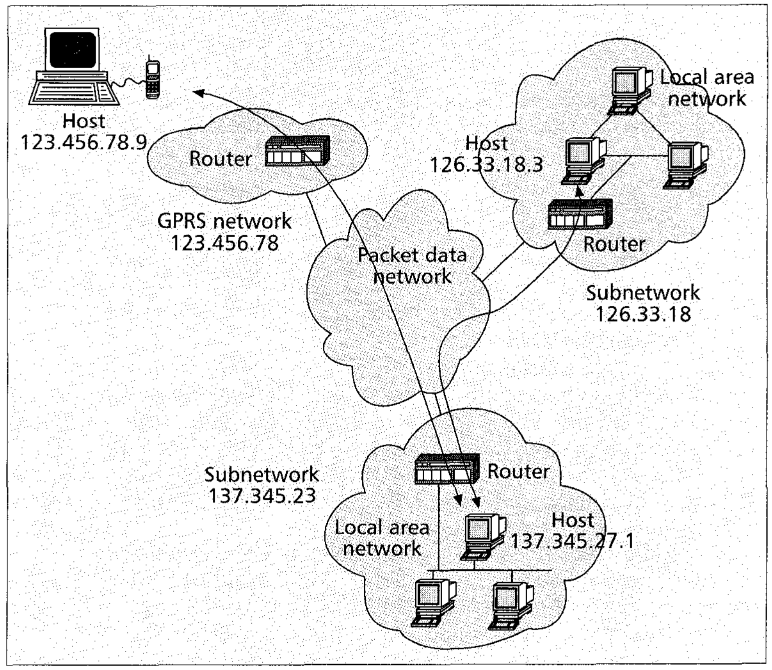


Figure 1. *GPRS seen from the user's point of view.*

Wireless PCs or so-called mobile offices should support any conventional Internet-based application, like file transfer, transmission and reception of e-mail, or "surfing" the Internet via the World Wide Web. Video is being perceived as a key element of multimedia services, and a considerable amount of standardization effort has been focused on the task of reducing bandwidth demands. The recently completed International Telecommunications Union — Telecommunications Standardization Sector (ITU-T) Recommendation H.263 specifies a low-bit-rate video compression algorithm, while International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) MPEG-4 has entered a collaborative phase. Based on these standards and on video hardware chips for the mobile environment that have recently been developed with compression rates of up to 80 percent, even transmission of video information (e.g., for video conferencing) seems to be applicable for GPRS.

Another very important application area is represented by road traffic and transport informatics (RTTI) applications. GSM/GPS (Global Positioning System) based automatic fee collection (AFC) systems are already within the test phase. These systems use the GSM short message service (SMS) for information exchange. GPRS is well suited to replace SMS, or may at least be used as an SMS bearer. Distribution of traffic control information such as road and weather conditions or route guidance and parking management are other RTTI applications which could be served by GPRS.

The international railway body, the Union Internationale des Chemins de Fer (UIC) intends to replace the existing incompatible national train control systems by a GPRS-based European train control system (ETCS).[1]

Other possible applications are connected to financial transactions. Electronic cash or fund transfers do not have very high communication requirements, and GPRS could be used as a bearer for these applications as well.

Because of capacity constraints caused by the available GSM bandwidth, transmission of very large data volumes by packet switching would significantly increase the blocking rate. Hence, GPRS should especially consider transmission of small data volumes. Various electronic devices, either static or mobile, could be equipped with a GSM/GPRS transceiver. Applications could be notification of alarms, collection of sensor values, and delivery of statistics, for example.

Thus, the range of possible applications for GPRS (Table 1) covers simple *distribution* and *messaging services* as well as advanced *retrieval* and *conferencing services* that provide multidirectional communication via real-time information transfer between multiple users.

Appl. \ Char.	Area	Type
WWW	Mobile office	Retrieval
FTP	Mobile office	Retrieval
E-mail	Mobile office	Messaging
Telnet	Mobile office	Conversational
Video	Mobile office	Conferencing
Fund transfer	Telematics	Tele-action
Alarm notification	Telematics	Tele-action
Auto. debiting	RTTI	Dispatching
Route guidance	RTTI	Distribution
Fleet mngmt.	RTTI	Dispatching

Table 1. *Possible GPRS applications.*

The transmission characteristics of these applications vary from frequent transmissions of small volumes to infrequent transmissions of small or medium data volumes. In general, the message size is below 500 bytes, but in some cases, like file transfer, the length may even be on the order of several kilobytes.

To satisfy these different application needs, a reasonable packet service should provide both connectionless and connection-oriented point-to-point (PTP) packet mode transfer as well as multicast and group call point-to-multipoint (PTM) services. Invocation of these different types of service requests should be supported from both fixed and mobile access points

[1] *As part of GMS Phase 2+, circuit-switched voice group call and voice broadcast call services are being standardized. Because of possible similarities these advanced speech call items (ASCI) have been reviewed within ETSI SMG GRPS ad hoc. For details the reader is referred to G. Brasche, "Prototype Implementation and Evaluation of New Packet Data Protocols for GSM," Dissertation, Aachen University of Technology, Germany, 1997.*

where applicable. Moreover, both data access to and interworking with different public standard data networks is a prerequisite for data applications to be served reasonably. Naturally, this requires provision of appropriate security features as well.

Class \ Size	128 octets		1024 octets	
	Mean delay	95%	Mean delay	95%
1 (predictive)	0.5 s	1.5 s	2 s	7 s
2 (predictive)	5 s	25 s	15 s	75 s
3 (predictive)	50 s	250 s	75 s	375 s
4 (best effort)	Not specified			

■ **Table 2.** *GPRS QoS attributes.*

Thinking about the design of packet-oriented data services, most important to network providers and operators is how cheaply the new services can be integrated into the existing networks. Therefore, one fundamental requirement should be to develop the new services as an extension of existing GSM tele- and bearer services, and to modify GSM network components as moderately as possible.

A variable quality of service (QoS) should be regarded as another important requirement that strongly influences the attractiveness of GPRS. Additionally, in order not to endanger profitability of traditional services, a new set of services should be provided rather than replacing or duplicating existing GSM services. This implies the need for independent operation and parallel use of GPRS with conventional GSM services. Consequently, it is important to consider an economical and adaptive use of available bandwidth according to the actual network load and application requirements.

SERVICE CHARACTERISTICS

Since GSM has been designed for circuit-switched transmission only, introduction of a packet-switching technique obviously evokes some significant functional and operational changes. Before these technical issues are treated, a closer look at the GPRS service characteristics specified so far reveals that the requirements connected to a GPRS are met satisfactorily.

Regarding the offered service, GPRS allows the subscriber to send and receive data in an end-to-end packet transfer mode, without using any network resources in circuit-switched mode. This allows for autonomous operation of GPRS and best fits the bursty traffic characteristics. Packet routing and transfer within the public land mobile network (PLMN) is supported by definition of a new logical network node called a *GPRS support node* (GSN).

The feature to set up multiple PTP dialogues and maintain these over long periods of time for background applications is considered by the possibility of establishing multiple parallel sessions. During these sessions PTP nondialogue and/or PTM communication will be possible in parallel. In addition to parallel GPRS sessions, simultaneous use of GPRS and traditional circuit-switched GSM services, including SMS, will be provided. Depending on available bandwidth and mobile station (MS) capabilities, parallel simultaneous use is correlated with degradation of the QoS or even call rejection.

For the coordination of circuit- and packet-switched services, an association between the GSM mobile switching center (MSC) and the GSN is created. This association is used to keep routing and location area information up to date in both entities. Furthermore, it enables combined GMS/GPRS attachment as well as paging of circuit-switched calls within the GPRS network. Exchange of short messages via GPRS is considered by connecting the GSM SMS-MSC to the serving GSN (SGSN), too. Although transmission of packetized speech would be possible, this has been outside the scope of GPRS thus far.

Aspects of flexibility are covered by online configuration of radio resources dedicated to GPRS by the network operator without interruption of service. The possibility of responding to local data traffic conditions adaptively is via the logical channel concept, which will be described later.

These network dynamics are completely hidden to the subscriber, although different service profiles in terms of throughput, delay, and priority can be negotiated between service provider and subscriber. Throughput, peak, and mean bit rates can be negotiated, while transfer delay and priority[2] are classified by four QoS classes. Three classes predictively specify the mean transfer delay and 95 percent delay, as shown in Table 2. The fourth class does not induce any delay value.

Handling of these QoS parameters is subject to radio resource management by means of service disciplines that support priorities.

The QoSs are correlated to multiple subscriber profiles. In contrast to the existing GSM, GPRS subscription management is service-specific; that is, users can activate each service to which they are subscribed separately. Charging is based on subscription fees paid regularly for a fixed period and traffic fees paid as a function of data volume, type of service request, and QoS. The charging method will be similar to those used in existing packet data networks (PDNs).

Regardless of the subscriber profile and QoS negotiated, data reliability in terms of residual error rates for lost, corrupt, duplicate, or out-of-sequence SDUs is specified to be 10^{-9} for group communication and in the range of 10^{-4}–10^{-5} for multicast communication. This is ensured by appropriate error detection and correction procedures performed by the protocols at the GPRS air interface U_m.

With the traditional GSM, the international Signaling Switch No. 7 (SS7) network is used for information exchange between different operators. Security is based on network access control without applying specific security methods. Within GPRS, the potential risk for intruders is higher since there is a larger number of possible access points, and interworking with public data networks like the Internet will be supported.

In order to protect the system against misuse of resources by unauthorized persons and eavesdropping on the information being exchanged on the radio path, the basic security principle follows that already used in GSM. Security is provided between the network elements by authentication, ciphering, and use of firewalls, instead of using extra security protocols. A temporary logical link identity provides user confidentiality.

Similar to existing GSM networks, service access will be possible while roaming between networks, provided a suitable international signaling mechanism exists. The roaming itself is supported by GPRS-specific gateways to be installed between two GSM networks depending on the operators' roaming agreement.

As already suggested, GPRS will offer data transfer capabilities between two MSs, or between an MS and various terminals, attached to either the GPRS network or the external PDN. Two types of services will be supported, PTP and PTM. The PTP service will be offered either connectionless or con-

[2] *The transfer delay includes the uplink radio channel access (or downlink radio channel scheduling delay), the radio channel transit delay, and the GPRS network transit delay; delays caused by fixed networks or other PLMNs are not considered. The priority indicates the importance of the packet with regard to discarding it in case of problems and degradation of QoS when necessary.*

nection-oriented. The first type is a datagram-like service, intended to support bursty noninteractive applications based on the connectionless network protocol according to ISO 8473 Connectionless Network Protocol (CLNP) [3] or the Internet Protocol (IP) defined by Request for Comments (RFC) 791 [4]. With this service, single and independent packets are sent from a single subscriber to a single destination user. The second type of service provides a logical relationship between users and is intended to support bursty transactional or interactive applications based on X.25 [5] or the Connection-Oriented Network Protocol (CONP) according to ISO 8348 [6].

The PTM service enables the transmission of a single message to multiple subscribers. Data transmission to multiple destinations is initiated by a single service request. The PTM service is subdivided into a multicast service (PTM-M) and a group call service (PTM-G).

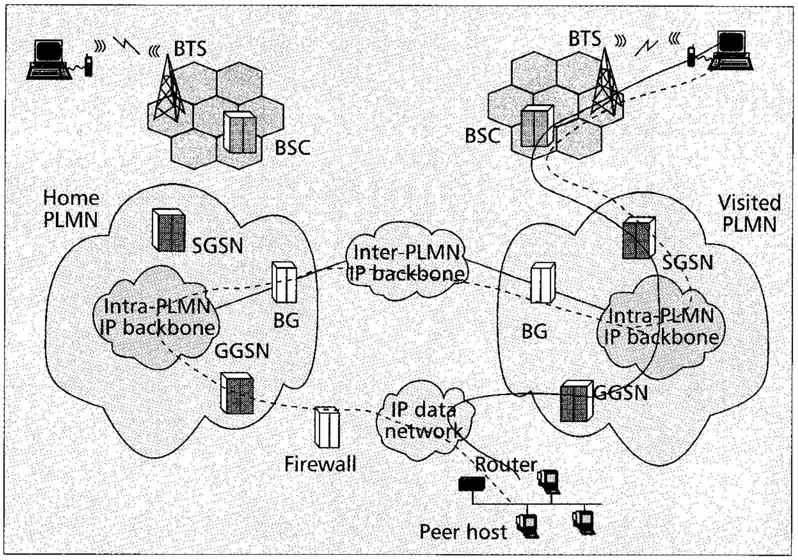


Figure 2. *Simplified routing example.*

Multicast means the message is addressed to all subscribers in a geographical area. The message contains a group identifier, indicating whether the message is of interest to all subscribers or only a subset belonging to a specific PTM group. With PTM-G only a predefined group of subscribers controlled by a multicast server will receive the message transmitted.

In order to serve the different needs of various market segments, three MS classes are defined, each with distinct capabilities. These MS classes fulfill the service characteristics introduced above to a certain predefined extent, and are referred to as class A, class B, and class C.

Class A represents the high-end MS. It is intended to support full simultaneous use subject to QoS requirements. Class B supports parallel use with the restriction that virtual calls will not be cleared down due to service invocation or traffic of circuit-switched services; the status of the connection is then assumed to be busy. Simultaneous traffic is not supported by this class. The user can make and/or receive calls on either of two services sequentially. Class C is matched to the low-cost requirements of the mass market and does not support simultaneous or parallel use at all; either GPRS or circuit-switched service can be selected. Anyway, class C MS will optionally have the capability to receive and transmit SMS messages. This implies that the network will support this option in any case.

Packet Data Routing

The existing GSM network does not provide adequate functionality to support packet data routing. Therefore the conventional GSM structure has been extended by a new class of logical network entities: the GSNs. The gateway GSN (GGSN) acts as a logical interface to the external PDNs and maintains routing information used to tunnel PDUs to the SGSN that is currently serving the MS. The functionality of the PTM service center (PTM-SC) to handle the PTM service is included within the GGSN.

The SGSN is responsible for the delivery of packets to the MSs within its service area. For several years the Internet community has been working toward a mobile extension of IP. The Mobile IP (MIP) concept does not meet the GPRS requirements exactly, mainly because non-Internet packet data protocols (PDPs) like X.25 are not supported. Nevertheless, the GGSN and SGSN can be considered counterparts of the MIP home and foreign agents.

Figure 2 illustrates the routing procedure. In the case of a mobile-originated transmission, the SGSN encapsulates the incoming packets and routes them to the appropriate GGSN, where they are forwarded to the correct PDN. Inside, PDN-specific routing procedures are applied to send the packets to the corresponding host. Packets coming from a corresponding host are routed to the GGSN through the PDN based on the examination of the destination address. The GGSN checks the routing context associated with this destination address and determines the serving SGSN address and tunneling information. The packet is encapsulated and forwarded to the SGSN, which delivers it to the mobile station.

All GPRS user-related data needed by the SGSN to perform the routing and data transfer functionality is stored within the GPRS register (GR), which is conceptually part of the GSM home location register (HLR). The GR stores the routing information and maps the international mobile subscriber identity (IMSI) to one or more PDN protocol (PDP) addresses as well as mapping each PDP address to one or more GGSNs.

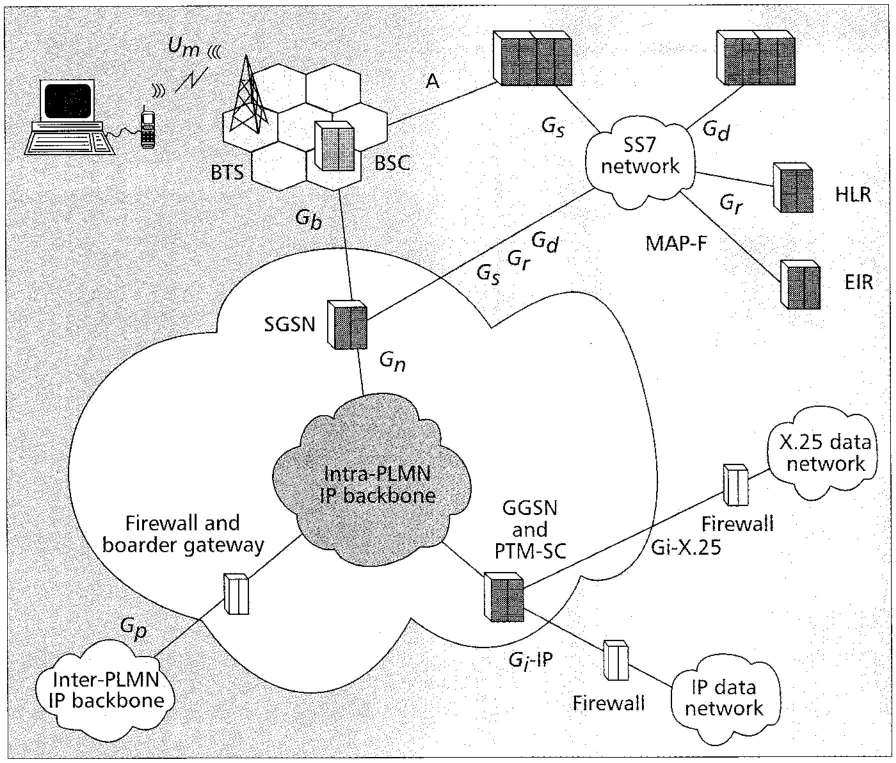
The resulting logical GPRS architecture, shown in Fig. 3, represents one possibility for adding these components to the GSM system. However, the crucial question during design has been how far the MSC is involved in the GPRS interactions, since this mainly influences the independence of network operators from NSS suppliers and decreases software and hardware investments. The presented proposal adopted by ETSI aims to minimize the MSC interactions.

Mobility Management

As may be derived from the description above, two different encapsulation schemes are used within GPRS: between the GSNs all packets are encapsulated by means of a common tunnel protocol in order to enable usage of different PDPs even if the protocol is not supported by all SGSNs. Encapsulation between the MS and SGSN is performed to decouple the logical link management from the network-layer PDPs.

Before an MS is able to send data to a corresponding host, it has to attach to a GPRS. With this attachment procedure carried out between the MS and SGSN, a logical link context is established. As a result, a temporary logical link identity (TLLI) is assigned to the MS. After attachment, one or more routing contexts for one or more PDPs can be negotiated with the SGSN. In order to verify that the MS is allowed to use a PDP, the GR is queried by the SGSN. The subscription information includes the matching GGSN address. If access is permitted, the GGSN is requested to update the routing context (i.e., serving SGSN address and tunneling information) accordingly.

During the GPRS session, the location of an MS is tracked



■ **Figure 3.** *GPRS architecture.*

plane up to layer 3 according to the ISO/OSI reference model. Above that layer, widespread standardized protocols may be used. The selection of these protocols is outside the scope of the GPRS specification. Recalling the transmission concept described above, GPRS will support interworking of MSs with X.25-, IP-, and CLNP-based networks and transmit the corresponding packet data protocol PDUs (PPDUs) transparently by encapsulation and decapsulation.

Between two GSNs, the GPRS tunnel protocol (GTP) tunnels the PDUs through the GPRS backbone network. The GTP header contains a tunnel endpoint identifier for point-to-point and multicast packets as well as a group identity for point-to-multipoint packets. Additionally, a type field in which the PDU type is specified and QoS parameter are included. Below GTP IP v. 4 is used as a GPRS backbone network-layer protocol. Depending on the operator's network architecture, Ethernet cabling, integrated services digital network (ISDN) links, or ATM-based protocols may be used below IP.

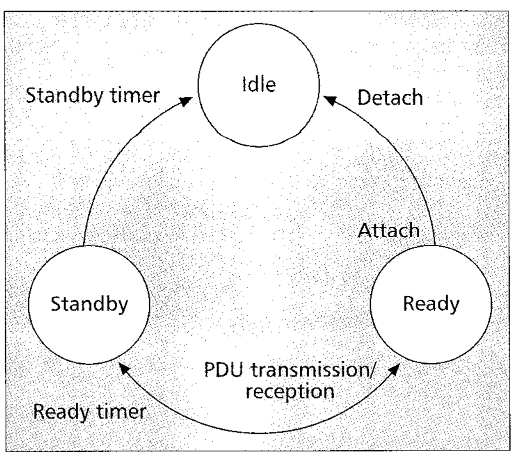
according to the three-state model shown in Fig. 4. While the MS informs the SGSN about every cell change when in *ready* state, location information is updated in *standby* state only if the routing area (RA) is changed. This routing area is a subset of the GSM location area and consists of an operator-defined group of cells.

A cell update is performed implicitly on the logical link control level. An update of location information is done by sending a routing update request to the SGSN. This request includes the identity of the new cell as well as the new and old RAs. An intra-RA update is performed when the SGSN handles both the old and new RAs. In this case, there is no need to inform the GGSN or GR/HLR since the routing context does not change. If the old RA is served by another SGSN, this new SGSN inquires the old SGSN to send the MM and PDP context of the MS. Afterward, GGSN and GR/HLR are informed about the new routing context, and the MM and PDP contexts are removed by the old SGSN.

Protocol Architecture

The GPRS data communication architecture adheres to the well-known principle of protocol layering and distinguishes between two protocol planes. The signaling plane consists of protocols that control and support the transmission of user information. GPRS-relevant functions are connection control, routing, and mobility management, already touched upon. The transmission plane covers the protocols for user information transmission and associated control procedures like flow control or error handling.

Data Transmission — Figure 5 shows the proposed transmission



■ **Figure 4.** *Mobility management state model.*

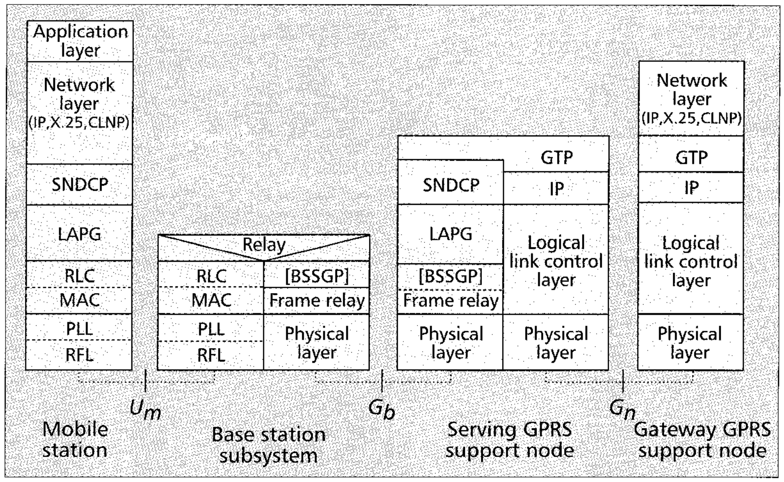
Between the SGSN and MS, further encapsulation is performed by the subnetwork-dependent convergence protocol (SNDCP) that maps network-level protocol characteristics onto the underlying logical link control and provides multiplexing of multiple layer 3 messages onto a single virtual logical link connection. Furthermore, ciphering, segmentation, and compression functionality are covered by SNDCP. The BSS GPRS protocol (BSSGP) has been derived from the BSSMAP already used in GSM, and conveys routing and QoS-related information between the BSS and SGSN.

Radio communication between the MS and the GPRS network covers physical and data link layer functionality. According to the standard proposal, the physical layer is split up into a physical link sublayer (PLL) and a physical RF sublayer (RFL). The RFL conforms to the GSM 05 series recommendations, and performs the modulation and demodulation of the physical waveforms. The carrier frequencies, radio channel structures, and raw channel data rates are specified, as well as transmitter and receiver characteristics and performance requirements.

The PLL provides services for information transfer over a physical channel between the MS and the network. These functions include data unit framing, data coding, and the detection and correction of physical medium transmission errors.

The data link layer has been separated into two distinct sublayers. The radio link control/medium access control (RLC/MAC) sublayer arbitrates access to the shared medium between a multitude of MSs and the network. The RLC/MAC layer encompasses the efficient multiplexing of data and signaling information, and performs contention resolution, QoS control, and error handling. The MAC itself is derived from a slotted reservation ALOHA protocol, and operates between the MS and BTS. For retransmission of erroneous frames, an automatic selective repeat request (SREJ-ARQ) mechanism is applied.

The logical link control (LLC) layer operates above the MAC layer, and provides a logical link between the MS and SGSN. To allow introduction of alternative radio solutions without major changes to NSS it is independent of the RLC/MAC protocol as far as possible. Protocol functionality is based on LAPD as used within the GSM signaling plane, but, for example, supports point-to-multipoint transmission. According to common terminology, the protocol is called *link access procedure on the G-channel* (LAPG).



■ **Figure 5.** *The GPRS transmission plane.*

Signaling — Between the MS, BSS, and SGSN (Fig. 6), the same protocols are used as for data transmission up to the SNDCP protocol. Only at the network layer, a specific mobility management protocol (MMP) is required within MS and SGSN to support the mobility functionality as previously described.

Signaling between the SGSN and HLR/SMS-MSC does not impose any GPRS-specific functions up to the mobile application part (MAP), and standard GSM signaling protocols can be used as shown in Fig. 7. The MAP has to be extended according to the GPRS mobility management. Between the SGSN and MSC an extended BSSAP is used instead of TCAP.

THE MSDRA MAC PROTOCOL

In this section, a MAC protocol for the GPRS air interface is described. The master-slave dynamic rate access (MSDRA) protocol has been developed at the ComNets Institute according to the draft ETSI standard of the GPRS air interface [1] and can be considered a GRPS RLC/MAC prototype implementation.

CHANNEL CONCEPT

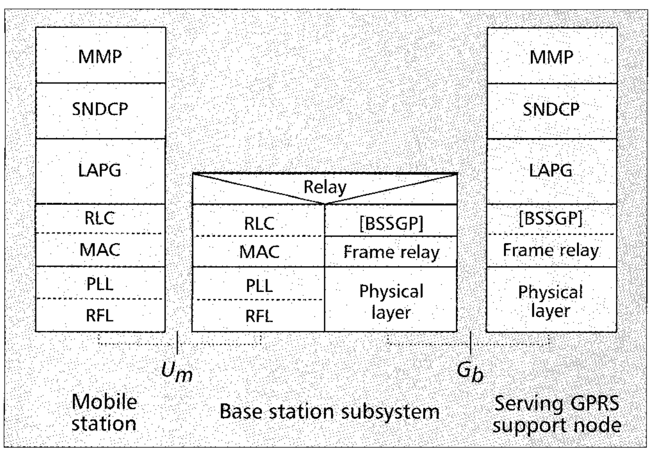
When a network operator decides to offer GPRS-based services within a cell, one or several physical channels from the pool of available channels are dedicated to packet mode transfer. Each of these so-called packet data channels (PDCHs) is mapped onto one physical time slot. According to the requirement for flexible adaptation to different traffic conditions, allocation of PDCHs is based on demand. Furthermore, uplinks and downlinks are basically used as independent channel resources; that is, in one time slot an uplink PDCH may carry data from one MS, while data to another MS is transmitted on the downlink PDCH. In order to simplify the logical channel concept, the allocated PDCHs are logically grouped into master and slave channels (MPDCHs and SPDCHs). The SPDCHs represent the channels on which user data and dedicated signaling is transferred:

- Packet traffic channels (PTCHs) are temporarily allocated traffic channels dedicated to one MS or a group of MSs used for user data transfer.
- Packet-associated control channels (PACCHs) transport signaling information (acknowledgments, timing advance, resource allocation) related to one MS.
- Packet data broadcast channels (PDBCHs) are used on the downlink in order to broadcast user data.

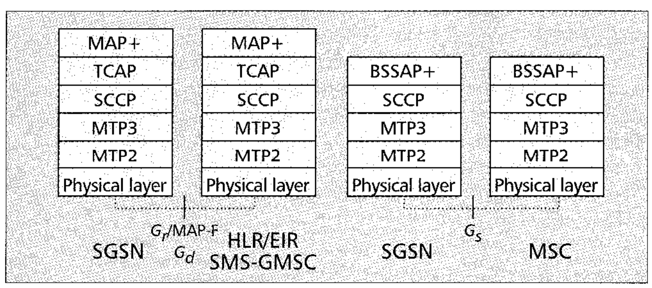
MPDCHs accommodate common control channels (CCHs) that carry the signaling information required to initiate packet transfer:

- The packet random access channel (PRACH) is used exclusively on the uplink in order to initiate data transfer of the MS.
- The packet paging channel (PPCH) is used exclusively on the downlink in order to inform MSs about incoming packets.
- The packet paging response channel (PPRCH) is used exclusively on the uplink in order to respond to paging.
- The packet access grant channel (PAGCH) is used only on the downlink to send channel reservation information to an MS prior to data transfer.
- The packet broadcast control channel (PBCCH) is used only on the downlink to broadcast all GPRS-specific information.

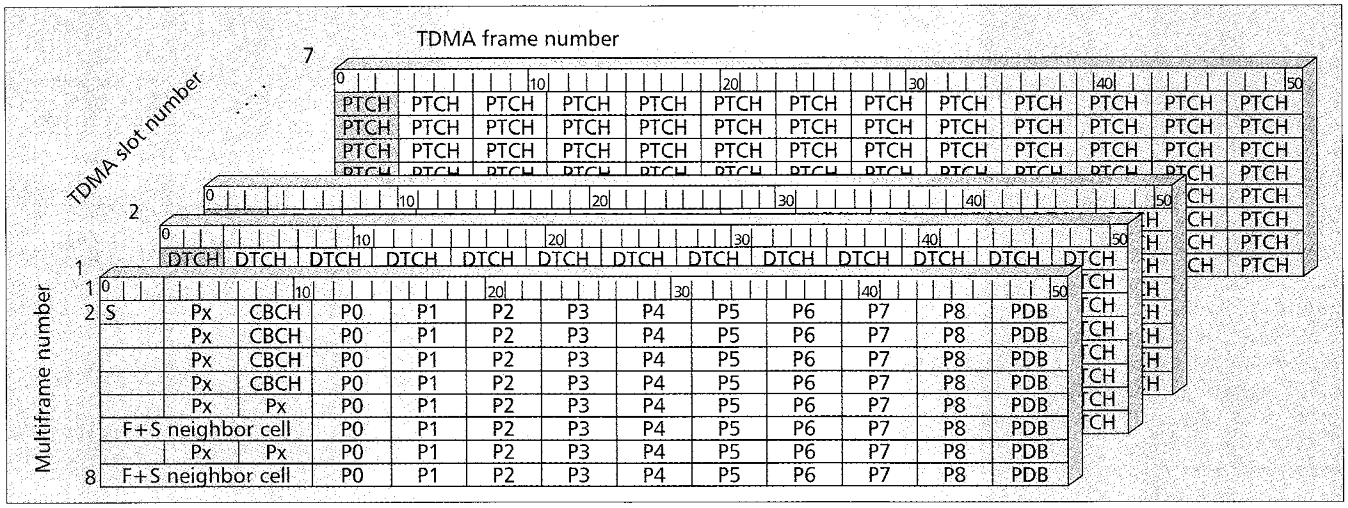
With the 26- and 51-multiframes there are two multiframes defined in GSM. As shown in Fig. 8, a 51-multiframe has been chosen for PDCH. The reason not to choose a 26-multiframe is that an MS has to listen not only to PDCHs but also to the synchronization, cell broadcast, and broadcast control



■ **Figure 6.** *Signaling protocols, SGSN–MS.*



■ **Figure 7.** *Signaling protocols, SGSN–HLR/MSC.*



■ **Figure 8.** *Example of MSDRA multiframe structure.*

channels (SCH, CBCH, and BCCH) to monitor GSM system-related parameters.

By use of a 51-multiframe, these channels will occur at given positions, since they use the GSM 51-multiframe structure. Even for neighboring cells the channels will occur at fixed position with an unknown offset only. This implies that some periods have to be reserved for reading neighbor BCCHs. During this period, the MS is unreachable for incoming messages. Moreover, similar to the BCCH cycle defined in GSM, a cycle has been selected that comprises eight multiframes.

The first multiframe of a cycle is divided up into 12 blocks of four frames. The first 11 frames are allocated to carry control information, while the remaining 10 blocks are allocated for paging and broadcasting. Within the other seven multiframes, three frames are dedicated to random access on uplink (PRACH), while all others represent a PTCH.

Model of Operation

An LLC PDU to be transferred over the air interface is segmented into one or more RLC frames, which are handed over to the MAC layer. Each MAC frame is transmitted as one block of four consecutive TDMA slots. A selective ARQ mechanism controls retransmission of erroneous or missing blocks by use of a temporary frame identity (TFI). The TFI further contains a job identification in order to allow multiplexing several jobs onto one PTCH.

Organization of slot assignment to the different MSs is done centrally by the BS. The channel reservation includes the time slot number and an uplink status flag (USF) coded by 3 bits. Thus, this USF can be used to multiplex up to eight different MSs onto one slave channel. An MS monitors the USF and starts transmission depending on its assigned USF value. The USF is transmitted at the beginning of each RLC block. On the MPDCH, multiplexing of up to three MSs is allowed.

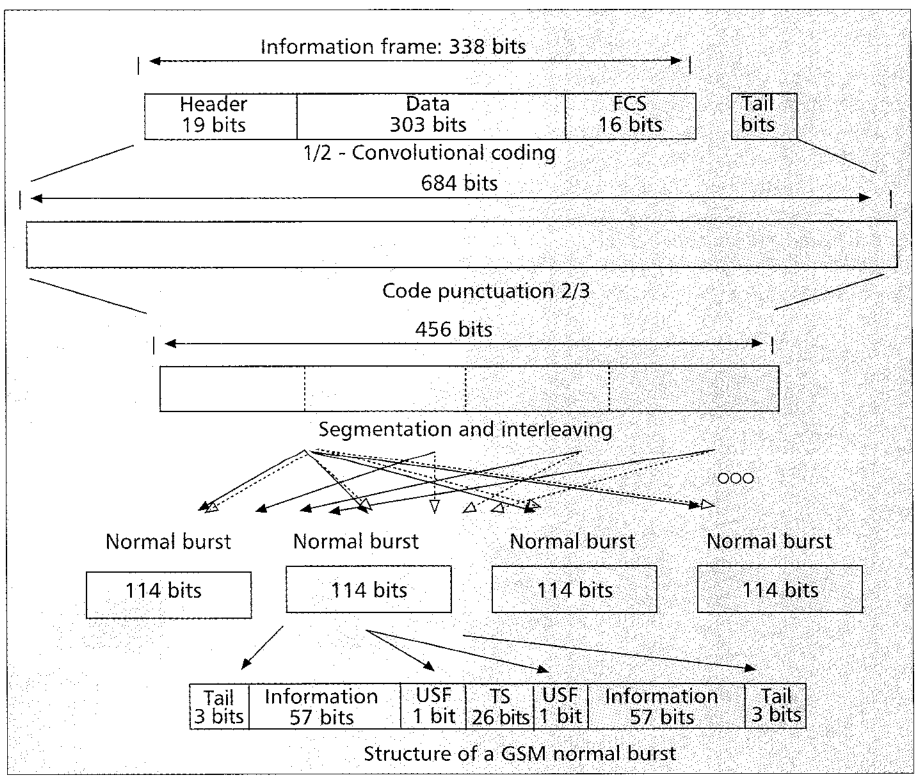
Provided this MS is multislot-capable, blocks of one MAC frame can be sent on different SPDCHs simultaneously. By this multislot reservation, the packet delay can be reduced and the bandwidth assigned to one MS can be varied dynamically. Thus, the status flags not only result in a highly dynamic reservation but also allow transmission to be interrupted in favor of pending or high-priority messages.

Medium access is based on a slotted ALOHA reservation protocol; that is, there are three phases on the uplink:

- Contention phase — A slotted-ALOHA random access technique is used to transmit reservation requests.
- Notification — The BTS transmits a notification to the MS indicating the channel allocation for a pending uplink transmission.
- Transmission — The data transfer occurs without contention.

On the downlink, there are two phases:

- Notification — The BSS transmits a notification to the



■ **Figure 9.** *Coding of user data.*

MS indicating the channel allocation for a pending downlink transmission.

- Transfer — The MS monitors the indicated channels, and the transfer proceeds without contention.

MOBILE-ORIGINATED TRANSFER

Packet transfer is initiated by a random access request on the PRACH that is determined by USFs sent on the corresponding downlink MPDCH. Together with the access request, the MS indicates the number of GPRS slots required.

Upon correct receipt of the access request, a channel reservation command is sent by the BTS where the reserved slots are marked, and timing advance and TFI are included. Since the capacity of the PAGCH is limited, not all correctly received access requests can be served directly. Nevertheless, to avoid superfluous resending, the affected MSs are informed about receipt and later channel reservation by use of an access grant notification message that may be concatenated with the channel reservation message to another MS. Furthermore, since the blocks are sent in descending order, the BTS always knows how many blocks are still to be received and may adjust reservation scheduling.

If no response to an access request is received by an MS, a retransmission procedure is started after a random backoff time up to a maximum number of access attempts.

After transmission in the reserved time slots is completed, an acknowledgment is sent by the BTS. With erroneous or missing blocks, a negative ACK (NACK) is sent, and only those blocks listed as erroneous are retransmitted. For that reason, this NACK directly includes an appropriate channel reservation. This implies that a NACK can be retransmitted with onlyminimal delay, since the BTS directly recognizes missing MS data retransmission on the first prereserved time slots.

If the MS does not receive an ACK within a certain time, frame transfer recovery is started by a new random access. Within the random access, the reservation of one single slot is indicated. After access is granted, the first block of the frame is sent. Thus, the BTS knows that the last ACK belonging to this frame transfer was not correctly received and should be retransmitted. In order to enable frame recovery, the frame and associated information about received and acknowledged blocks should be kept to a minimum value of several seconds.

MOBILE-TERMINATED TRANSFER

A BTS initiates a packet transfer by sending a page on the PPCH. If the BTS knows the location of the MS, this may include either a direct reservation of uplink slots for uplink transmission or an indication of downlink slots for data reception. Thus, an MS responds by either sending a random access request on the PRACH or immediately starting data transmission/reception on prereserved slots. If the location is only known to a certain degree of probability, the BTS does not reserve slots for immediate data transmission but avoids the collision-sensitive random access procedure by reservation of a single slot for a paging response that precedes the channel reservation. If a page without reservation is made, the MS initiates the random access and asks for a reservation of one block to be able to identify itself after access is granted.

As far as multiplexing, multislot downlink transmission, and error handling are concerned, the BTS has the same functional possibilities as an MS. Of course, whether more than one downlink PDCH assigned to the GPRS can be used for parallel transmission depends on the MS's capability to monitor these PDCHs simultaneously.

Code rate	USF	RLC block	CRC	Tail bits	Code bits	Punc. bits	Data rate
1/2	3	181	40	4	456	0	9.05
⊕ 2/3	6	266	16	4	584	128	13.3
⊕ 3/4	6	314	16	4	680	224	15.7
1	12	428	16	0	456	0	21.4

■ **Table 3.** *Coding parameters.*

BURST FORMATS AND CODING

Four different coding schemes are defined to be able to adaptively react to current channel quality. Figure 9 illustrates the coding principle. The first coding scheme equals the SDCCH coding used in GSM: 1/2-rate convolutional coding and a 40-bit fire code are applied. This scheme is used for all signaling messages. The second and third schemes are punctured versions of the first one with rates of 2/3 and 3/4, respectively. The fourth coding scheme does not apply a convolutional coder. The latter three schemes use a 16-bit frame check sequence for error detection. The resulting coding parameters and maximum bit rates are shown in Table 3.

In order to speed up decoding of USF, schemes 2–4 generate a 12-bit block USF code word. For schemes 2 and 3 this is achieved by precoding the USF into a 6-bit block word before applying convolutional coding to the whole block without puncturing the first 12 bits. Using scheme 1, the entire block is coded, and USF must be decoded as part of the data.

The coding scheme is indicated by the GSM stealing bits of the four consecutive bursts that belong to one block using an 8-bit block code with a Hamming distance of 5.

The random access and paging messages are sent by use of the existing GSM random access burst., while data transmission is done with GSM normal bursts.

SIMULATION

In the following, some simulation results will be presented for both single- and multislot access. The results focus on the frame transfer delay (FTD), *throughput* (*S*), and *blocking rate* (*B*). For further evaluation criteria (e.g., frame access delay, channel utilization, or dropping rate), see [7].

SIMULATOR TOOL

For the performance evaluation of the MAC protocol, an event-driven simulator has been implemented using the Institute's C++ class library CNCL [8].[3]

In the actual implementation, the simulator focuses on the U_m interface only, and thus simulates communication between MS and BSS. The required functionality of SGSN is included within BSS. The two base classes, MS and BSS, are each linked to a group of classes that represent the GPRS protocol stack. The actual protocol functionality is implemented within the network, LLC, and MAC classes. The communication principle between the layers follows the principles of the reference model for open systems interconnection of the ISO: service data units (SDUs) and interface control units (ICUs) are used for vertical communication, while PDUs are used for horizontal communication. Integration of protocols, formally specified using the ITU-T functional specification and description language (SDL) [9], is

[3] *CNCL has been developed to support event-driven simulation. It is available free of charge according to the spirit of the GNU Library General Public License via anonymous ftp@comnets.rwth-achen.de.*

possible by means of an SDL interface. The use of such a formal description technique (FDT) during software development should be state of the art since it ensures code reusability and simple modification and maintenance. The MS and BSS are connected via two independent downlink and uplink classes in which the physical layer model is implemented. This modular design allows different protocols as well as radio channel models to be investigated without major changes to the simulator structure.

Characteristics of the physical channel such as fading and interference are modeled by means of ETSI pattern files, which are used to determine bit and packet error rates. Due to the use of puncturing, a pattern file generator has been implemented that generates a code-scheme-specific pattern. Correct receipt of a collided packet is provided by an adjustable capture model. Moreover, a graphical user interface enables visualization of the protocol behavior and channel state over time.

According to ETSI SMG GPRS ad hoc evaluation guidelines, different traffic load models have been implemented. The FUNET model (Fig. 11) is based on statistics collected on e-mail usage from the Finnish University and Research Network. The probability distribution function can be approximated by a Cauchy distribution, with a maximum message size of 10 kbytes:

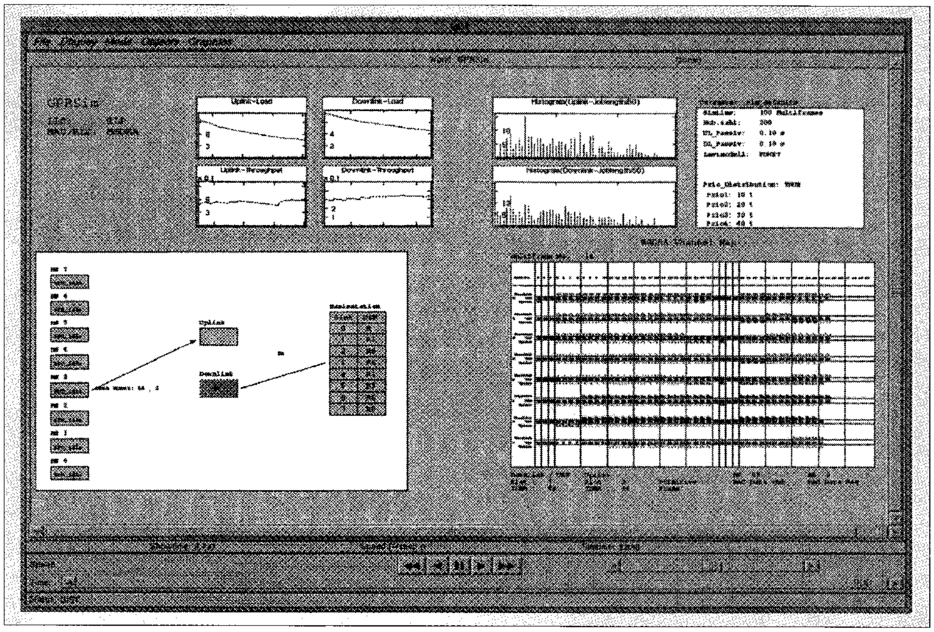
$$\text{Cauchy}(0.8,1) = f(x) = \frac{1}{\pi(1+(x-0.8)^2)}$$

The Mobitex model is based on statistics collected from a fleet management application using the Mobitex wireless packet data network in Sweden:

Uplink: 30 ± 15 bytes   *Downlink*: 115 ± 57 bytes

The Railway model (Fig. 12) is based on an assessment of railway application requirements. An approximation of the cumulative distribution function with an average message length of 170 bytes and a maximum length M of 1000 bytes is:

$$F(x) = P(x \,''\, M); F(x) = 1 - e^{-x/170} \qquad (3)$$



■ **Figure 10.** *Graphical interface of the GPRS simulator tool.*

Basic Assumptions and Evaluation Criteria

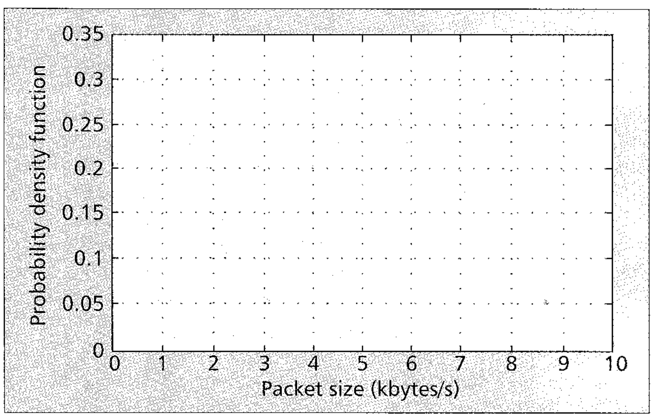
The simulations presented in this article were carried out with the following main simulation parameters:

- Simulation time: 200 multiframes
- Number of MSs: 200
- Response time, BSS/MS: two TDMA frames
- MS state: active, that is, no additional paging delay
- Number of GPRS channels: 8
- Maximum number of PTCs allocated to one MS: 4
- Retransmission counter : 7
- Coding scheme: 3, that is, code rate 3/4

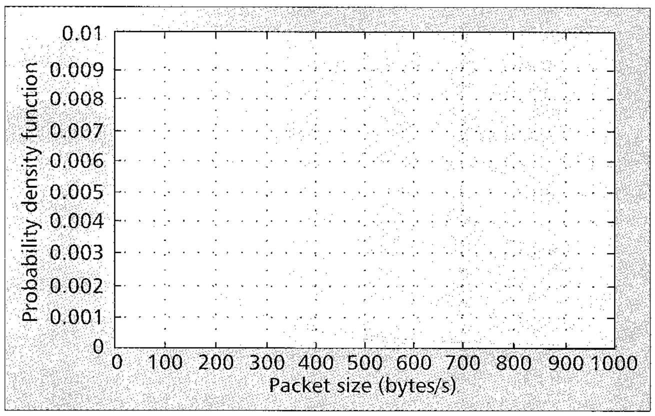
During the contention phase, the following capture model is assumed: If n is the number of access bursts sent during the same period on a single channel, the probability p of successful receipt related to one burst is:

- $p = 1.00$ for $n = 1$
- $p = 0.67$ for $n = 2$
- $p = 0.48$ for $n = 3$
- $p = 0.40$ for $n = 4$
- $p = 0.35$ for $n = 5$
- $p = 0.00$ for $n > 5$

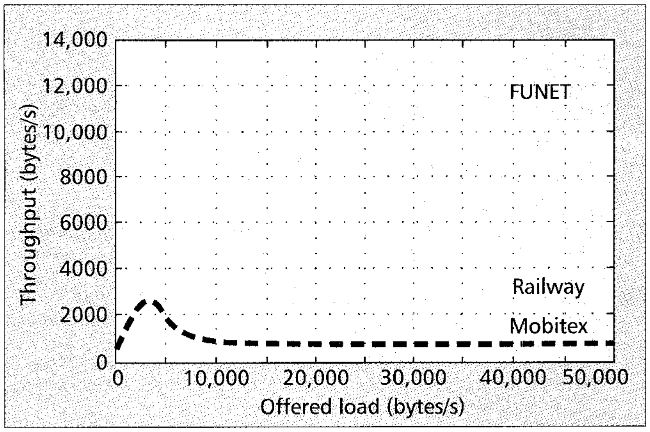
Concerning the evaluation criteria, the following definitions apply: the *frame transfer delay* specifies the time period between an MS sending an LLC frame and the BSS receiving it. The *throughput* (S) is the amount of data per second that



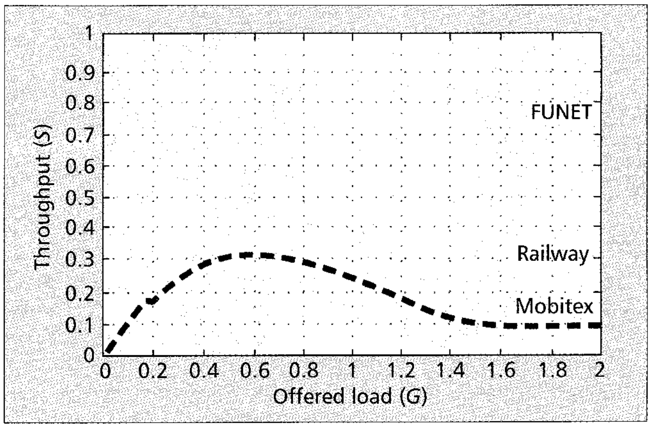
■ **Figure 11.** *The PDF of the FUNET model.*



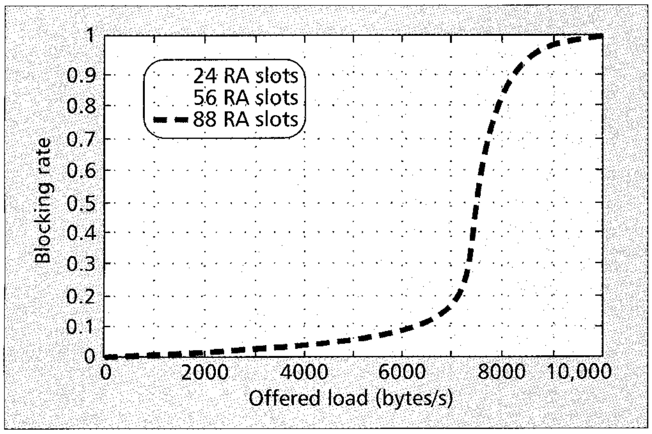
■ **Figure 12.** *The PDF of the Railway model.*



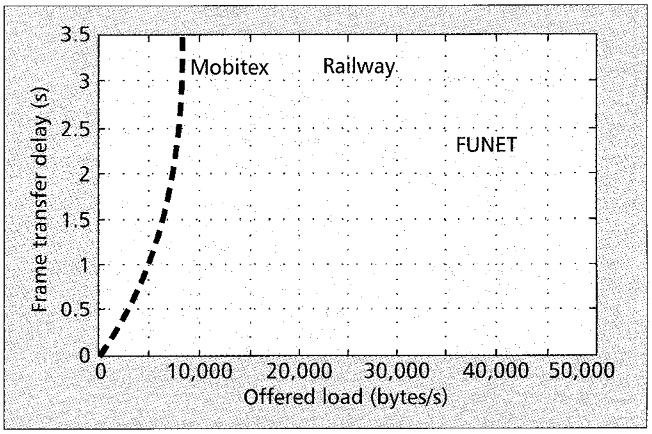
■ **Figure 13.** *Throughput with single-slot assignment.*



■ **Figure 14.** *Throughput with multislot assignment.*



■ **Figure 15.** *Blocking rate.*



■ **Figure 16.** *Frame transfer delay, single-slot.*

has been successfully transmitted over the air interface, while the *offered traffic load* (G) indicates the normalized amount of generated data related to the channel capacity. The *blocking rate* (B) indicates the probability that a random access sent by an MS has not been successfully received.

Simulation Results

Figure 12 shows the throughput in relation to the offered load for the different channel models in the case of single-slot and multislot assignment. As can be seen, there is no significant difference between single- and multislot throughput.

With FUNET, 70 percent of the maximum theoretical throughput can be achieved, while the Railway and Mobitex models result in 48 and 30 percent only. Under high load conditions, the implemented channel resolution algorithm that equally spreads out the collided random access bursts over the next cycle is not capable of handling collisions anymore, and the protocol becomes unstable. This is strongly correlated with the three random access slots at the beginning of each multiframe.

The reason for the smaller maximum throughput in the case of traffic generated according to the Mobitex and Railway models is the generated packet sizes. The Mobitex model generates packets that fit in one or two data blocks. Hence, much more packets have to be generated at high load, although capacity of the second block remains unused because of the small message size.

Since each RLC block implies a random access attempt, more collisions occur. Furthermore, relative to the generated amount of data, more signaling information in the form of acknowledgments and channel reservation needs to be transmitted. The Railway model generates packets up to 1000 bytes long, but an analysis of the probability distribution function shows that most of the packets are smaller than six blocks, and the same argumentation as for the Mobitex model can be applied.

The influence of the number of slots available for random access can be seen in Fig. 13. Within this figure, the blocking rate is depicted for a varying number of random access slots in the case of the Mobitex traffic load model and multislot assignment. Especially for short Mobitex messages, the number of possible RA slots significantly influences the blocking rate and throughput. While three RA blocks already result in a blocking at 4000 bytes, offered traffic can be handled up to 7000 bytes with 11 RA blocks.

Figure 14 illustrates the FT delay for both single and multislot assignment. As may be supposed, the FT delay is smaller in the case of multislot assignment, since the time between slots belonging to one transmission is shorter due to the parallel assignment.

Conclusions

In this article the basic concepts and service features of a general packet data service for integration into the existing GSM system have been described under consideration of the current standardization activities of ETSI SMG ad hoc GPRS.

Based on the proposed GPRS data communication architecture, the GPRS air interface principles have been explained and a corresponding medium access control protocol has been introduced within the framework of a protoype implementation. A simulative performance analysis showed reasonable performance for long packets. The master-slave channel concept in combination with the multiplexing strategy lead to flexible protocol behavior under different load conditions.

Nevertheless, the multiframe structure is still not optimized for small data packets and should be modified. This has been recognized within ETSI SMG as well, and the latest standard proposal includes a new 52-multiframe structure that is under implementation. Other optimization is related to, for example, channel allocation, backoff strategy, and QoS handling.

At the moment, the simulation tool is being enhanced with regard to its group communication simulation facilities. For that purpose a multimedia traffic generator concept and missing SGSN functionality is being implemented. Thus, it will be possible to simulate the performance of GPRS in case of inter cell communication. Since standardization is still ongoing, further modifications and improvements will be considered, as well.

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Biographies

GÖTZ BRASCHE (gb@comnets.rwth-aachen.de) received his M.S degree in computer science from Aachen University of Technology, Germany in 1991. He joined the Institute for Communication Networks of the same university as a Ph.D. candidate in electrical engineering in 1992. Since August 1994 he has been involved in the development of new packet data services for existing and future digital mobile radio networks. Within this research area he finalized his Ph.D. thesis in June 1997.

BERNHARD WALKE received his Diploma and doctor's degree in 1965 and 1975, both from the Department of Electrical and Electronics Engineering, University of Stuttgart, Germany. From 1965 to 1983, he first served at the AEG-TELEFUNKEN Research Institute at Ulm/Germany and later as a department head in the AEG Division for High Frequency Techniques, where he evaluated performance of computer systems and designed computer based data communications networks. In 1983 he joined the Department of Electrical and Electronics Engineering at Fern University of Hagen as a full professor for data processing techniques and, in 1990, Aachen University of Technology as a full professor for communication networks. His scientific work comprises about 80 scientific papers and five textbooks, in the fields of modeling and performance evaluation of computer and communication systems. In 1975 he earned the ITG-Best Paper Award.