THE ROOTS OF GPRS: THE FIRST SYSTEM FOR MOBILE PACKET-BASED GLOBAL INTERNET ACCESS

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ABSTRACT

GPRS, the General Packet Radio Service in GSM was the enabler of the mobile Internet. The origins of key radio access functions employed for packet-switching in GPRS are identified by reviewing state-of-the-art on random access protocols applied in cellular radio data networks existent or proposed before GPRS specification started. A table is provided showing the degree of conformance to GPRS of the respective systems. Besides the type of demand assigned multiple access protocol used in a system, dynamic placement of control channels to the packet data channel and statistical multiplexing of fractions of IP packets of simultaneously transmitting mobile stations to the same packet data channel appear to be key differentiators, besides others. CELLPAC by comparing its functions to that of GPRS is shown to comprise what is called here the Fundaments of the GPRS Radio Interface Protocol. The history of ETSI GPRS standard development is described. Although GPRS is a result of cooperation of many actors which contributions are valued, it appears possible to identify the roots of its radio access protocol and thereby main contributors.

INTRODUCTION

The General Packet Radio Service (GPRS) was launched worldwide in 2001 as a service provided by the Global System for Mobile (GSM) to provide mobile Internet access. Later, adaptive modulation and coding for higher data rate was introduced to GPRS under the name Enhanced Data Rate for GSM Evolution (EDGE), leaving the access protocol unchanged. Concepts enabling packet data communication in cellular radio networks were kept and further developed from GPRS/EDGE when specifying 3G Universal Mobile Telecommunications System (UMTS) and 4G system Long Term Evolution (LTE).

EARLY CONCEPTS FOR WIDE AREA MOBILE DATA NETWORKS

The architecture of a Public Land Mobile Network (PLMN) is shown in Fig. 1, where the Access Network (AN) is made-up from Mobile Stations (MSs) connected to the Base Station Subsystem (BSS) across the Radio Interface (RI). The BSS is part of both AN and Core Network (CN), and comprises multiple Base Stations (BSs) each serving a radio cell connected star-shaped to a Base Station Controller not shown in the figure. In the core network, mobility supporting functions are found like Subscriber Register (SR) responsible for roaming, authentication and billing of MSs, and switching nodes dedicated to circuit- and packet-switched services, respectively. Gateway Circuit-/Packet-Switched Exchange nodes hosting Interworking Functions (IWFs) shown in Fig. 1 interface to external networks to connect a MS to MSs of other PLMNs and to fixed subscriber terminals.

PLMNs support roaming where the MS's current location is stored in SR so that an incoming call can be routed to a MS. Roaming requires the MS to update SR when entering another cell not belonging to the location area of the previous cell. Advanced PLMNs besides roaming also support handover for keeping service quality of a MS when communicating on the move. Handover provides continuation of communication within and across cells with small service interruption, only.

Roaming of movable wireless terminals (WTs) connected directly by protocol IEEE 802.11 WLAN to the Internet is provided by Mobile Internet Protocol versions 4 (MIPv4) and MIPv6. Since Internet access routers typically do not provide cellular radio coverage, roaming of WTs is supported only when associated to an access router and handover of WTs is not provided at all. Therefore, wireless networks are not considered to be mobile networks.

The network elements shown in Fig. 1 have its own protocol stack for both control and user data exchange. PLMNs differ much in the protocol stacks used at the RI but extensively rely on fixed network protocol stacks known from PDNs. What is PLMN specific are network elements for mobility management in the core network and the protocol stack at the RI. The focus in this study is mainly on the protocols applied at the RI in the access network.

Mobile stations having data to send will request transmission at random times. Since MSs have no knowledge of each other's existence or status, management of the mobile random-access to the uplink (UL) channel by

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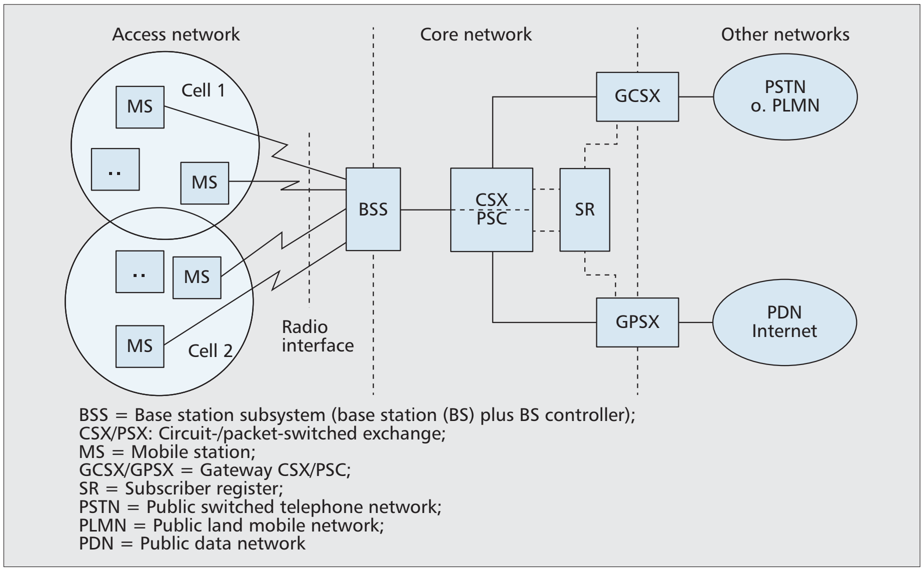

Figure 1. *Generic architecture of a cellular mobile radio network (PLMN).*

Mobile packet-switched networks enable MSs to exchange packet data over radio. Besides stand-alone networks there exist packet-switched networks integrated to circuit-switched networks occupying some of its radio channels.

multiple concurrent MSs is a major challenge in radio access protocol design. Aloha and slotted (S) Aloha are the simplest multiple-access protocols to a mobile radio channel, but these are considered inefficient when used for data transfer, where MSs contend directly with their data messages. In [1] it is shown that radio access protocols that combine S-Aloha request channels with separate traffic channels can achieve very high utilization in a stable way. Typically, a request channel has only to transmit small amounts of control data and so requires a small bandwidth compared to the user data channels. If sufficient bandwidth is allocated to the request channel for it to operate stable (at low utilization) then the data channels may be operated at high utilization. This is the reason why modern mobile radio networks provide random access control channels besides traffic channels (TCHs) to carry speech and user data transfer.

Mobile Circuit-Switched Data Networks — Mobile networks originally were designed for circuit-switched speech communication and later offered data as an add-on. A simple form of mobile data communication is data transmission using modems over analog cellular telephone links. In this form of communication, the mobile user accesses a cellular channel just as he would in making a standard voice call over the cellular network. Mobile terminals typically operate at 9.6–14.4 kb/s data rate using error correction protocols like MNP-10, V.34, and V.42 for reliable data transmission. Modem-based circuit-switched transparent data service was provided by analog and digital cellular networks, e.g., EIA-553 AMPS and ETSI GSM shortly after start of the respective network. The user then operates the modem just as would be done from office to office over the PSTN. In this form of communication the network is not actually providing a data service but simply a voice link over which the mobile data modem can interoperate with a corresponding data modem in an office or computer center.

A data modem uses a traffic channel on the RI in the same way as the voice service. A traffic channel for exclusive use for the data transfer of one mobile user is reserved when the data arrives. It will be released when the data message is transferred. This traffic channel is established between the MS and the Interworking Function (IWF) located in the GCSX in Fig. 1.

Data transmission on top of an underlying cellular telephone service has limitations imposed by the characteristics of the voice-circuit connection. The service might be cost effective if long data files are transmitted on a connection. However, the service is costly if only short messages are exchanged over the network during a (long) session supporting an interactive service, where the circuit-mode connection is mostly unused but charged by the operator. This is the reason for development of mobile data networks that apply end-to-end packet switching based on, e.g., X.25, IP or proprietary protocols.

Mobile Packet-Switched Data Networks — Mobile packet-switched networks enable MSs to exchange packet data over radio. Besides stand-alone networks there exist packet-switched networks integrated to circuit-switched networks occupying some of its radio channels.

Before work started to specify GPRS in 1993, a number of concepts were known for packet or message switching in a mobile radio network as discussed in the following. But first, multiple-access (MA) protocols to a request channel are introduced.

ALOHA, S-ALOHA, DAMA

The birth of mobile radio and MA to a radio channel dates back to 1897 when Marconi was credited with the patent for wireless telegraph.

DAMA-based systems with explicit reservation in response to a request sent on a contention channel assign an UL TDMA channel for packet data transmission by explicit communication to the MS via a DL control channel. The PDCH typically is then different from the contention channel.

Marconi MSs mounted on ships, sharing the same radio channel were the first to contend to a shared channel for transmitting a sequence of Morse coded telegraphy characters. Like with the Aloha protocol Marconi MSs repeat transmission if no response is received to a message sent.

In 1970 the ALOHANET was opened to connect multiple low data rate stations through a single radio channel to a central host. For that purpose the MA-protocol Aloha [2] was designed, where stations transmit their data packets at random times. Under Aloha the station having a data packet ready transmits it on the channel to the central host without considering any synchronisation or access rule. The packet also contains identification, control and parity check information. Packets sent by different stations may partly overlap and collide at the receiver. A station waits for a time-out to happen or for receiving an acknowledgement from the central host. After time-out the packet is retransmitted after a random pause interval. This process is repeated until successful transmission or until the process is terminated by the station. The randomly transmitted Aloha packet is a user data message. It is not a signalling message to prepare for packet data exchange. In [2] it is shown that the effective channel capacity is 1/(2e).

The *S-Aloha* protocol proposed 1972 is applied to a time-slotted channel and thereby doubles channel capacity [3]. Stations apply the Aloha protocol but in addition are required to synchronise their packet transmissions into fixed length channel time slots. Thereby, partial overlap of packet transmission of different stations is avoided.

Most cellular radio data networks assign radio channels to MSs based on a demand-assigned multiple-access (DAMA) protocol [1] where an UL request channel is shared by many MSs through contention based on S-Aloha. A data channel is assigned by the BS in response to a successful request and the requesting MS will start to use the channel assigned for the duration of its data communication.

With the DAMA protocol, **user data on UL may be transmitted *outband* (*Uo*) on a TDMA channel different from the shared request channel, or *inband* (*Ui*)** on the shared channel.

Cellular systems based on DAMA protocol require, besides time-slotting, the channel to be organised in TDMA frames so that slots can be identified by their position in a frame. If the frame length is longer than the maximum channel propagation delay, each MS can be informed of the status of each time slot of the preceding frame. A slot in the frame provides a TDMA channel which may be used as a control or packet data channel (PDCH).

DAMA-based systems with *explicit reservation* in response to a request sent on a contention channel assign an UL TDMA channel for packet data transmission by explicit communication to the MS via a DL control channel. The PDCH typically is then different from the contention channel.

With *implicit reservation* a successful request by an MS on a contention channel is acknowledged by the BS on the corresponding DL channel. This results in an automatic reservation of the same channel used for the request to be used also for user packet data transmission on UL. Accordingly, two DAMA types on DL are to differ: *De* and *Di* for *explicit* (*e*) and *implicit* (*i*) realization, respectively, of the DL control channel granting a MS a data channel. Further, the DL control channel used to grant a MS a channel for UL packet data transmission may be realized *outband* or *inband* to the DL packet data channel corresponding to the potential UL data channel.

Therefore, four DAMA types on DL are to differ: *Deo* and *Dei* for explicit outband and explicit inband realization, respectively, of the explicit reservation channel. *Dio* and *Dii* for implicit outband and implicit inband realization, respectively, of the implicit reservation channel.

R-ALOHA and PRMA — R-Aloha [4] and PRMA [5] are DAMA protocols type (*Ui*, *Dii*). The R-Aloha protocol was designed to connect MSs generating long multi-packet messages via transponder based satellite systems to a central host. The channel is operated without central control since MSs can hear each other. In cellular radio networks where MSs cannot hear the UL channel central control by the BS is required to inform MSs via a broadcast control channel on the status of each slot of the forthcoming UL frame.

The PRMA protocol is widely known, although not implemented in a real system. There the DL control channel is assumed able to immediately broadcast to all MSs the status of an UL slot in a preceding frame. UL slots broadcast by the BS to be "available" for random access in a frame may be accessed by an MS. Collisions of MSs are resolved by back-off and repeated transmission. A successful MS is confirmed by the BS to use the slot that it had used for MA for data transmission as a TDMA channel in the next and subsequent frames until the MS's data expire.

Early Mobile Packet Data Networks

The most important early packet data networks discussed in the following were closed after GSM/GPRS started its operation in the respective region/country.

The Advanced Radio Data Information Service (ARDIS) full-duplex wide area packet-switched cellular radio service of Motorola and IBM that is based on Motorola *DataTAC* was launched in 1983 in large US cities [6]. The service connects MSs by radio under control of the proprietary Radio Data (RD) Link Access Procedure (LAP) offering 8kb/s user data rate. RD-LAP covers ISO/OSI network (layer 3) and link layer (layer 2). Connectionless and connection-oriented communication based on virtual circuits is supported. Mobility and radio resource management is provided covering roaming but not handover. RD-LAP layer 2 provides ARQ and access control at the RI by the Digital Sense Multiple Access (DSMA) protocol. With DSMA the BS provides in each DL slot, besides user data for a MS addressed in a slot, the channel status symbol (CSS) indicating whether the slotted UL channel is idle or busy. Free UL channels are used in contention mode to transmit a request packet. If a MS has data to transmit, it randomly waits up to 50 ms before it reads out the CSS. If CSS signals an idle UL channel, the MS transmits immediately its data as RD-LAP blocks, 12 byte each, resulting in a message of up to 512 byte transmitted. If the channel was detected busy, the MS waits for a random time-duration and then again looks for the value of the CSS. A collision during contention to the UL is resolved by a random back-off time until the MS retries again. During transmission of RD-LAP blocks by a MS the receiving BS transmits CSS = busy information on DL. DSMA is a DAMA (*Ui*, *Dei*) protocol. Packet data is transmitted by concurrent MSs one-by-one (Fig. 2) where one common traffic channel of a cellular radio system is alternatingly used as a PDCH by two MSs to transmit data packets with some idle gaps in between. The other common traffic channels may also be used as PDCHs or may be used for circuit-switched services.

The MOBITEX packet data service for digital speech and data communication developed by Swedish operator Telia and Ericsson was first launched in 1986 in Sweden providing country-wide cellular data services supporting roaming but not handover. Since in US the system was introduced by RAM Mobile Data in 1990 it is also known as RAM Packet Data Network. The RI data rate is 8 kb/s half-duplex supporting files of up to 20 kByte. The network layer supports datagram transfer by the proprietary protocol MPAK and the link layer provides ARQ. Access to the shared radio channel is by a DAMA protocol type (*Ui*, *Deo*) called Reservation TDMA. The BS on DL of the RI provides the number of slots of the FDMA channel available for random access [7]. A MS randomly picks a slot to transmit an access request on UL while the BS may send DL traffic. At the end of the period reserved for random access, the BS grants permissions to MSs one-by-one resulting in sequential transmission of data of concurrent MSs (Fig. 2).

The COGNITO cellular mobile packet switching network was operated until 2003 in UK for datagram transfer before it was replaced by GPRS [8]. MSs may transmit in slots or minislots (four to a slot). 64 byte user data are carried in a slot. Minislots are used for contention on UL and acknowledgement on DL. Periodic slots in the TDMA frame on UL and DL are dedicated by means of the Slot Map to be control or data channels. Random access is by S-Aloha to a control channel and collisions are detected by MSs from absence of an acknowledgement. The BS will acknowledge a request on UL and direct the MS to a free UL slot (TDMA channel to transmit its user data. This DAMA protocol is type (*Uo*, *Deo*). MS are served one-by-one, see Fig. 2.

Cellular Radio Integrating Circuit and Packet Switching

Concepts Not Implemented — Local Cellular Radio Network (LCRN) [9] is the first to integrate circuit-switched digital speech/data and packet-switched services in a mobile radio system based on FDMA/TDMA channels. Virtual connection and datagram service are supported. Some TDMA channels are provided for control and others for packet data transfer. S-Aloha is used for MA in a DAMA (*Uo*, *Deo*) protocol. The trunk of TDMA channels is dynamically assigned according to needs to circuit- and packet-switched services.

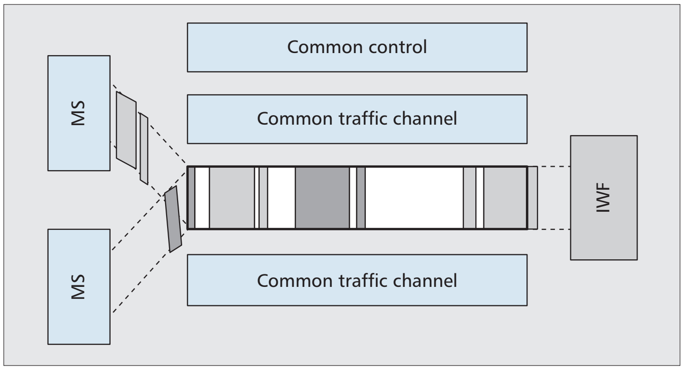

Figure 2. *Packet channel (PCH) reserved for the duration of a packet transfer of a single user.*

A cellular radio system integrating circuit- and packet-switched data transmission is introduced by Ken Felix [10] where channels can be used for voice, dedicated data or packet-switched data. Extensions to the signaling standard of US digital cellular phone standard (1993) TIA IS-54 are proposed to enable a mobile packet service. MSs transmit on a packet-switched radio channel one by one, see Fig. 2. Access to the UL channel is either through polling MSs by the BS, or by a MA protocol not specified in detail in [10], which appears to be DSMA. If polling is used, random access is switched off and the protocol is then not MA at all.

Improvements to PRMA are proposed in [11] by Mitrou (MLP) for an integrated system supporting both circuit- and message-switching voice and data. Slots of a TDMA-frame are dedicated to be control or data channels as known from PRMA and COGNITO. UL control slots used for MA are subdivided into minislots to each carry a miniburst request message. Once a request miniburst was successful, the MS is assigned by the BS a periodic packet data slot for the duration of its data transmission. The protocol is DAMA (*Uo*, *Deo*). MSs are served one by one as shown in Fig. 2.

Systems Implemented — The cellular digital packet data (CDPD) service was specified in 1993 as an overlay to the advanced mobile phone service (AMPS) [12] to provide 19.2 kb/s data rate. Some FDM channels of AMPS carry the connection-less CDPD service. MA at the RI by DSMA protocol prepares transmission of up to 64 blocks each 54 Byte without multiplexing data blocks of concurrent stations.

Standards TIA IS-54 and TIA IS-95 specify a three-slot per TDMA frame and a CDMA (code division multiple access cellular radio system, respectively. Like ETSI GSM, around 1992 these

	Packet-switching protocol suite	PS service in CS TDMA network	DAMA protocol type	Context estab. before data trx	Dynamic placement of UL/DL control on data channel	USF function	TA and PC for MSs sharing a TDMA channel	Statistical mux of MSs to TDMA channel	> 1 MS simula-tion con-trolled	Short ID carried in control and data channel
PRMA	–	–	*Ui, Dii*	+	–	–	–	–	–	0
ARDIS/ DSMA	(+)	–	*Ui, Dei*	+	(+)	–	–	–	–	0
Mobitex	(+)	–	*Ui, Deo*	+	+	–	–	–	–	0
Cognito	0	–	*Uo, Deo*	+	–	–	–	–	–	+
LCRN	(+)	+	*Uo, Deo*	+	–	–	–	–	–	0
Felix [10]	0	+	–	+	–	–	–	–	–	0
MLP [11]	(+)	+	*Uo, Deo*	+	–	–	–	–	–	(+)
CDPD	(+)	–	–	+	–	–	–	–	–	0
IS–54/95	+	–	*Uo, Deo*	+	–	–	–	–	–	0
[17]	(+)	+	*Uo, Deo*	+	–	–	–	–	–	(+)
CELLPAC	+	+	*Ui, Dei*	+	+	(+)	+	+	+	+
GPRS	+	+	*Ui, Dei*	+	+	+	+	+	+	+

– : not applicable; 0: not fulfilled; +: fulfilled.

Table 1. *Comparison of proposed/implemented packet-switched data networks.*

networks were prepared to carry circuit-switched data services besides speech. Data services were offered from about 1993/94 on, where a channel is dedicated to a point-to-point connection. Since many mobile data applications generate bursty traffic, market acceptance of the service was low. In all these systems a channel is shared by MSs on a call by call basis. A DAMA (*Uo*, *Deo*) protocol is used to provide circuit-switched-data service.

CELLPAC: A First Version of GPRS

To ease understanding of GPRS, the *Fundaments of the GPRS Radio Interface Protocol ("GPRS Fundaments")* are introduced in the following with reference to the roots where the respective functions were proposed first. The first full GPRS specification Release '99 provided in 200 kHz bandwidth a symbol rate of 271kb/s resulting in 22.8kb/s data rate of a full-rate TDMA traffic channel (TCH). Multi-slot operation is an option. In a later GPRS Release (EDGE) the data rate of a TCH increased to 69kb/s.

It appears that most *GPRS Fundaments* have been first proposed for CELLPAC [13–15] introducing packet-switching in GSM. In what follows the CELLPAC functions are explained and compared to GPRS and to other systems known earlier. Table 1 (discussed later) summarizes the results.

GPRS is based on a new protocol for radio access and on provisions introduced to the GSM core network to enable packet data transmission [16]. Since packet-switched data networks and IP tunneling were known when GPRS was designed, the hardest part in designing GPRS was to introduce

- Packet radio access of GPRS enabled MSs without changing GSM layer-1 functions implemented in hardware.
- A protocol suite for the network elements of the access and core networks to support packet-switching.

Protocol Suite

Protocol stacks for network elements required for packet-switching did not exist in GSM [18]. Figure 3a shows the protocol suite with a protocol stack per network element as introduced in [15], which is close to GPRS, see Fig. 3b. It is worth noting that layer-2 at the radio interface (RI) U_m running on top of GSM physical layer (layer-1), in both protocol stacks shows two sublayers, namely Medium Access Control (MAC) in Fig. 3b, called "Packet Access" in Fig. 3a, and Radio Link control (RLC) in Fig. 3b called Radio Link Protocol (RLP) in Fig. 3a. In Figure 3a the MS is split into data terminal equipment (DTE) and mobile terminal (MT).

"Packet Access" protocol data units are transmitted across the RI in Fig. 3a called RLC/MAC data block in GPRS, see Fig. 8. The GPRS stack compared to that of CELLPAC is further optimized to contain the Logical Link Control (LLC) protocol, and the Sub-network-Dependent Convergence Protocol (SNDCP), both operating between MS and SGSN, not affecting the RI. In network layer (layer-3) ITU-T protocol X.25 is used in both CELLPAC and GPRS, besides IP. During specification of GPRS Rel.'99 it turned out that IP would be the major network layer protocol. An X.25 like virtual connection established during association of a MS to GPRS was kept to allow for fast link establishment of a MS having data ready to send. The virtual connec-

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