The Roots of GPRS: The first System for Mobile Packet based Global Internet Access[1]

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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.

1. <u>Introduction</u>

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).

1.1 Early Concepts for Wide Area Mobile Data Networks

The architecture of a Public Land Mobile Network (PLMN) is shown in Figure 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

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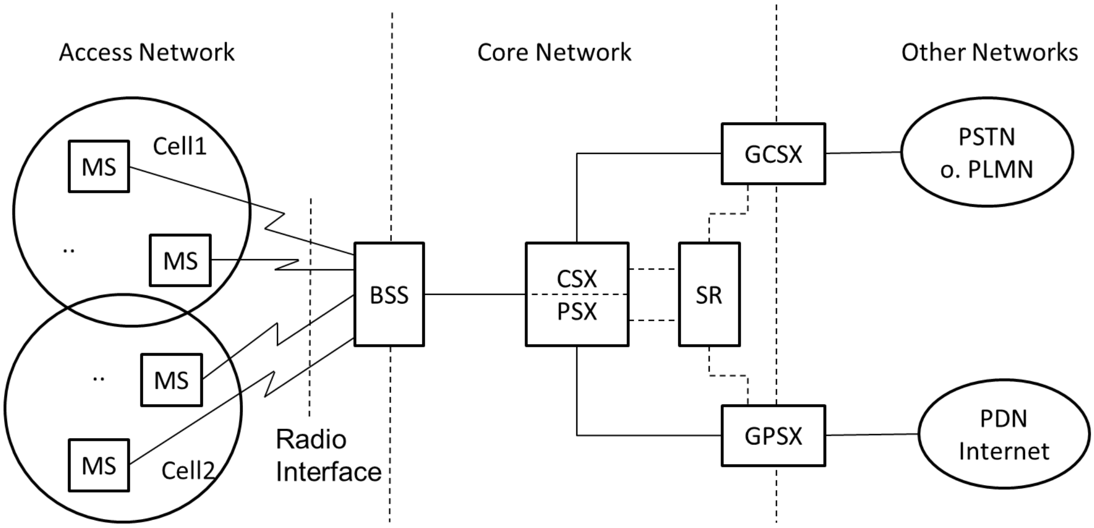
connected star-shaped to a Base Station Controller not shown in the figure. In the core network, mobility supporting functions are found like Subscriber Register (SR) responsible for roaming, authentication and billing of MSs, and switching nodes dedicated to circuit- and packet-switched services, respectively. Gateway Circuit- / Packet-Switched Exchange nodes hosting Interworking Functions (IWFs) shown in Figure 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.



BSS = Base Station Subsystem (Base Station (BS) plus BS Controller);

CSX/PSX = Circuit-/Packet-Switched Exchange; MS = Mobile Station;
GCSX/GPSX = Gateway CSX/PSX; SR = Subscriber Register;
PSTN = Public Switched Telephone Network; PLMN = Public Land Mobile Network;
PDN = Public Data Network;

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

The network elements shown in Figure 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 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 utilisation 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 utilisation) then the data channels may be operated at high utilisation. 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.

1.1.1 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 kbit/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 Figure 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.

1.1.2 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.

1.2 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. 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.

1.2.1 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.

1.3 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 8kbit/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 (see Figure 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 kbit/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, see Figure 2.

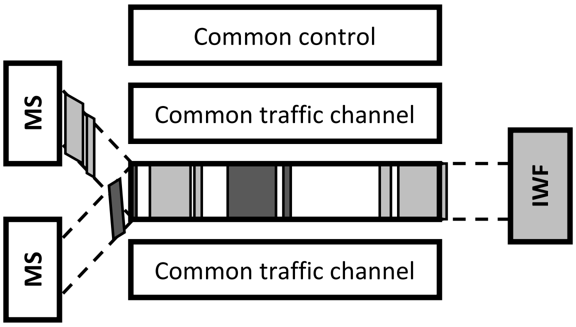


Figure 2: Packet channel (PCH) reserved for duration of packet transfer of single user

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 Figure 2.

1.4 Cellular Radio integrating circuit- and packet-switching

1.4.1 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.

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 Figure 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 Figure 2.

1.4.2 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 kbit/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 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.

2. 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 271kbit/s resulting in 22.8kbit/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 69kbit/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

(1) Packet radio access of GPRS enabled MSs without changing GSM layer-1 functions implemented in hardware.

(2) A protocol suite for the network elements of the access and core networks to support packet-switching.

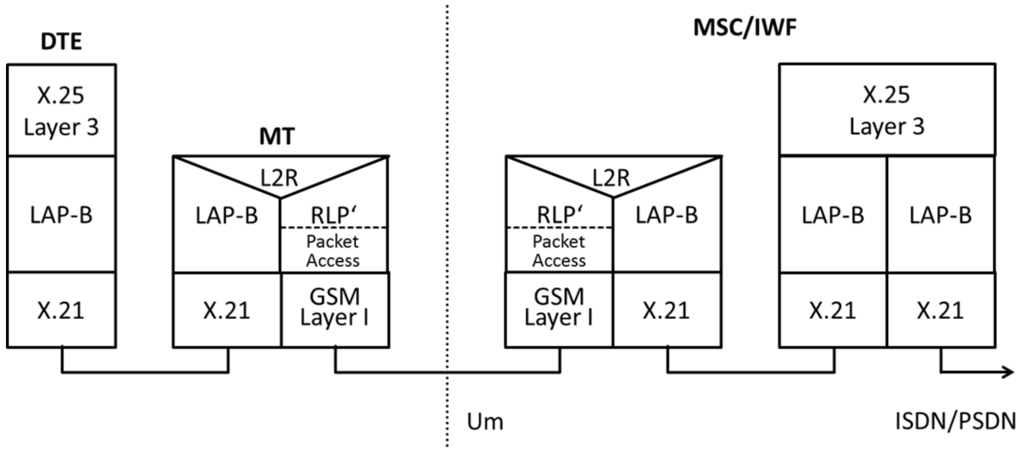
2.1 Protocol Suite

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 Figure 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 sub-layers, namely Medium Access Control (MAC) in Figure 3b, called 'Packet

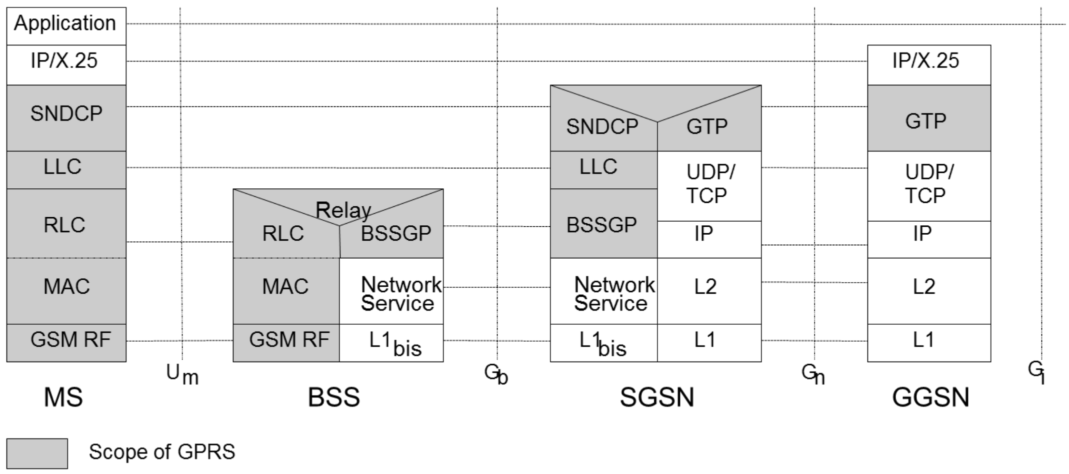
Access' in Figure 3a, and Radio Link control (RLC) in Figure 3b called Radio Link Protocol (RLP) in Figure 3a. There the MS is split into data terminal equipment (DTE) and mobile terminal (MT).

'Packet Access' protocol data units are transmitted across the RI in Figure 3a called RLC/MAC data block in GPRS, see Figure 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 connection later was specified as semi-permanent, thereby providing the '*Always On'* property of GPRS.

The protocol suite proposed in [15] was followed by the GPRS standard at the RI and in part in the core network.



a) PSDN = Packet Switched Data Network, MSC/IWF = Mobile Switching Center/Interworking Function



b) BSS = BS Subsystem, SGSN = Serving GPRS Support Node, GGSN = Gateway GPRS SN

Figure 3: Protocol Suites for CELLPAC (a) and GPRS (b)

Since the packet data rate in early GPRS is small (12 kbit/s) but Internet application protocols like SMPT, HTTP, etc. should be supported, the Wireless Application Protocol (WAP) was specified by the WAP Forum to enable '*Thin Clients'* with small screens to run Internet applications on MSs with low processing power across low rate data links [20].

GSM/EDGE with its data rate of up to 384kbit/s on smart communications devices enables Internet application protocols more comfortable.

2.2 GPRS as a Service in the Circuit-Switched GSM Network

GSM with its voice and data services was deployed when discussion started on how to realize a packet radio service. Eight physical TDMA radio channels per FDM channel are provided in GSM per transmit direction, see Figure 4. A time-slot may carry a Normal Burst (NB) as used by GSM control and TCHs, or may carry a Random Access Burst (RAB) or other burst type. In [13] - [15] one (or more) time slot of the GSM TDMA-frame representing in GSM a physical TDMA channel is dedicated as a combined packet data and control channel, called the CELLPAC dedicated TCH. *Thereby the GPRS Packet Data Channel (PDCH) is anticipated.*

Dedication of some TDMA channels of a circuit-switched cellular network for packet-switching is known from [9], [10], [12], and [18] of which [9] was the first to propose this.

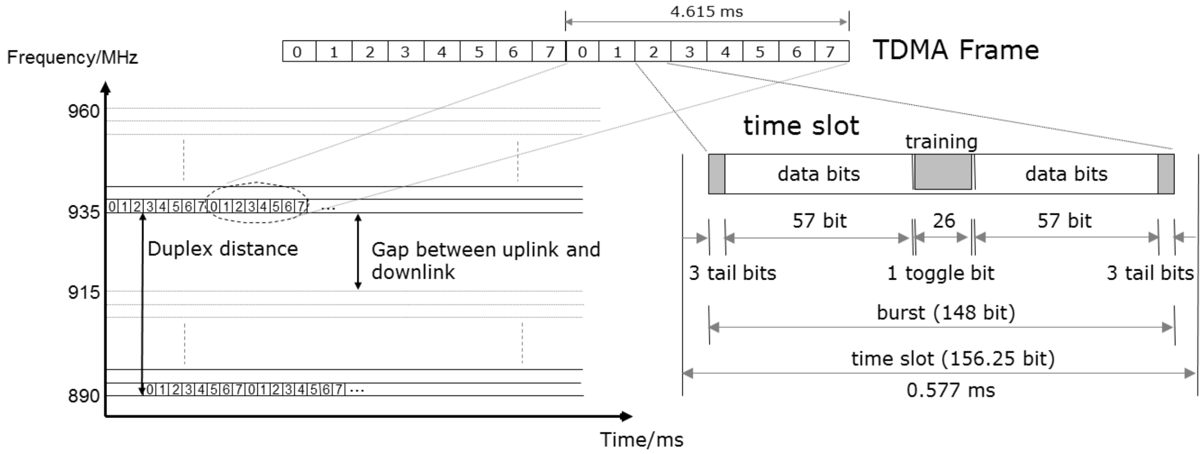


Figure 4: FDM and TDMA channels in GSM

2.3 PDCH Shared by Control and User Data

Multi-frames as known from GSM but with different structure are introduced in [15] for both UL and DL of the slot used as a CELLPAC TCH. A CELLPAC multi-frame specifies the roles of a slot of a TDMA-frame over time to be either control channel or packet data traffic channel (PDTCH), see Figure 5. The CELLPAC multi-frame comprises 26 GSM TDMA frames. In vertical direction slots 0 to 7 represent the respective TDMA frame. TDMA frames 13 and 26 of DL and UL, respectively, carry the fixed packet control channel (PCCH) on DL and the packet random access channel on UL. Slots on the DL may carry the PDTCH or the dynamic packet control channel (PCCH). UL slots may be reserved by the BS as PDTCH for a MS to transmit packet data or may be dynamically be dedicated for random access. GPRS specifies a 52 multi-frame.

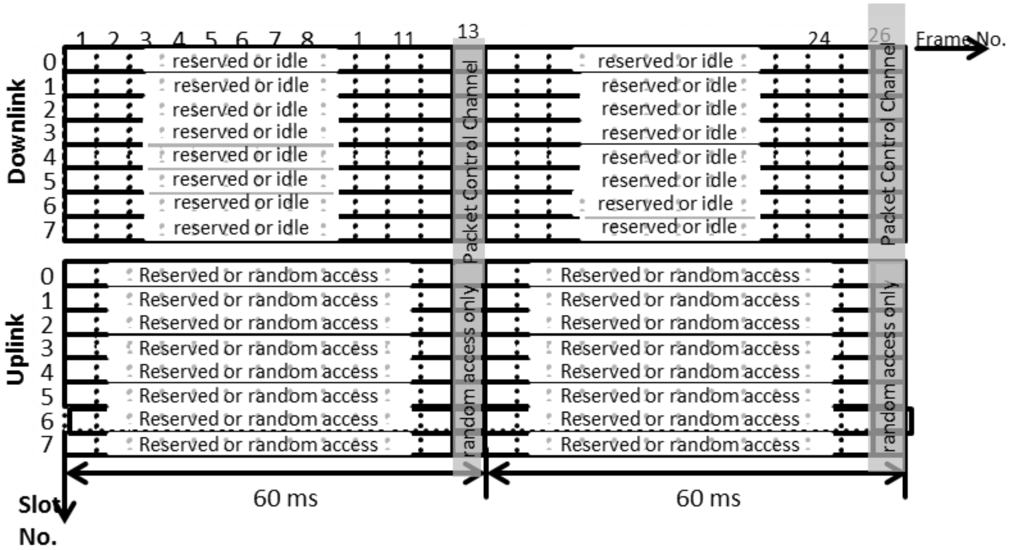


Figure 5: CELLPAC multi-frame. 'Reserved' means a slot is dedicated as PDTCH

Both the GSM control channels for virtual connection setup and the CELLPAC *dedicated TCH* are shown in Figure 6 [15]. The latter comprises logical control channels ('Access' and 'Control') and voice/data channels for packet data transmission. The logical channels mentioned correspond to Packet Random Access Channel (PRACH), Packet Common Control Channel (PCCCH) and Packet Data Traffic Channel (PDTCH) specified by the GPRS multi-frame to be carried on the Packet Data Channel (PDCH) that is a frame-periodic slot.

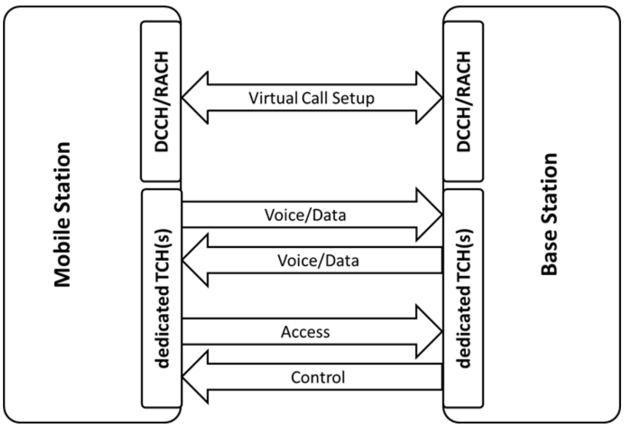


Figure 6: GSM Dedicated Control Channel **(DCCH) and Random Access Channel** (RACH) used for virtual call set-up, and dedicated Traffic Channel (TCH) for data transmission in CELLPAC [15].

No cellular packet-switched system besides GPRS applies a multi-frame for mapping logical control and data channels to one TDMA channel as introduced in [15].

2.4 Packet Data Context Establishment

Association of a MS to the mobile network and packet data context (PDC) establishment before transmitting GPRS packets avoids that radio resources have to be kept reserved in circuit-switched mode during transmission gaps. In GPRS radio resources are only assigned by the BS when needed to receive/transmit packet data by an MS, whereby the PDC is referenced in packets transmitted. GSM control channels and GSM protocols are used in GPRS for association of an MS to the network. Before an MS may transmit/receive packet data, establishment of the PDC between SNDCP entities of MS and SGSN, see Figure 3b, to be extended by the GPRS Tunnel Protocol (GTP) to the GGSN is also required. The PDC specifies the functions of a layer-2 logical link and relates it to the route of the respective layer-3 virtual connection.

Virtual connections based on X.25 are introduced by CELLPAC [14], [15] to connect MS and IWF, see Figure 3a using GSM signaling, before data packets are transmitted on the packet dedicated TCH assigned. Context establishment before data transmission was known before GPRS.

2.5 Control of two MSs by one DL Control Burst

The logical link between MS and BSS operated by the RLC/MAC protocol in Figures 3b carries RLC/MAC blocks, see Figure 8 and is known as GPRS Temporary Block Flow (TBF) identified by the TBF Flow Identity (TFI) carried in the block. TFI is unique among concurrent TBFs in a cell and replaces the complete GPRS MS identity known as Temporary Logical Link Identity (TLLI). Packet Transmission is performed in layer-3. In layer-2 segments of packets are transmitted as RLC/MAC blocks that we call packet data here.

The control burst (CB) transmitted in CELLPAC on PCCH has two sub-bursts, each comprising (1) 1 bit for uplink state indication (USI), (2) 8 bit identification of the packet data context by a 'MS Random Number' (MRN), (3) 6 bit for time advance info for slot synchronization, (4) 5 bit for power level and (5) 1 Paging Bit (PB), see Figure 7 [15]. The next and following UL slots for packet data transmission may be assigned to an MS by a control sub-burst with {USI=1, PB=1}. An MS may be informed to receive in the next and following DL slots packet data by a control sub-burst with {USI=1, PB=0}. Further, a MS may be paged to show-up to the BS by setting {USI=0, PB=1} to transmit a random access burst. UL channel reservation for packet data in CELLPAC by setting {MRN, USI=1, PB=1} functionally corresponds to the Uplink State Flag (USF) in GPRS. DL channel reservation for packet data by setting {MRN, USI=1, PB=0} corresponds to TFI in GPRS. RLC/MAC data blocks in GPRS carry both USF and TFI, see Figure 8. Data packets destined for MSs are queued by the BS.

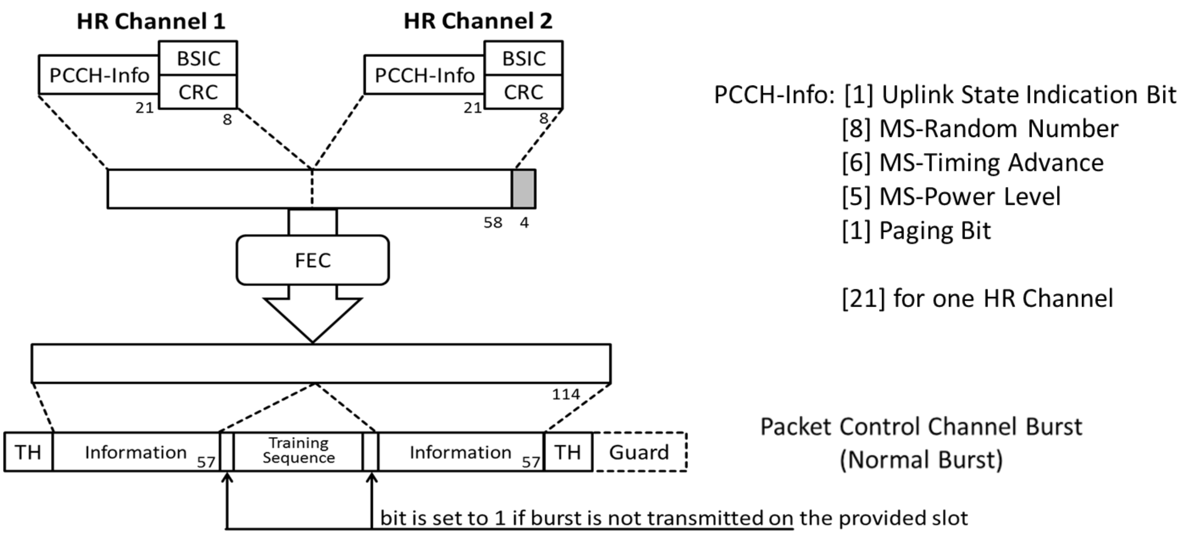


Figure 7: Packet Control Channel (PCCH) on DL of CELLPAC [15]

A PCCH CB in CELLPAC may provide control to two different MSs. The RLC/MAC header in GPRS, Figure 8, carries USF and TFI that also may address two different MSs.

CELLPAC [15] anticipates control of two MSs by one DL control message as used in GPRS.

Since the PCCH may be dynamically placed by the BS on any DL time slot of the CELLPAC multi-frame not reserved as a fixed DL control channel [15], consecutive DL slots may be used to transmit a PCCH message with interleaving depth four as known from GSM control messages.

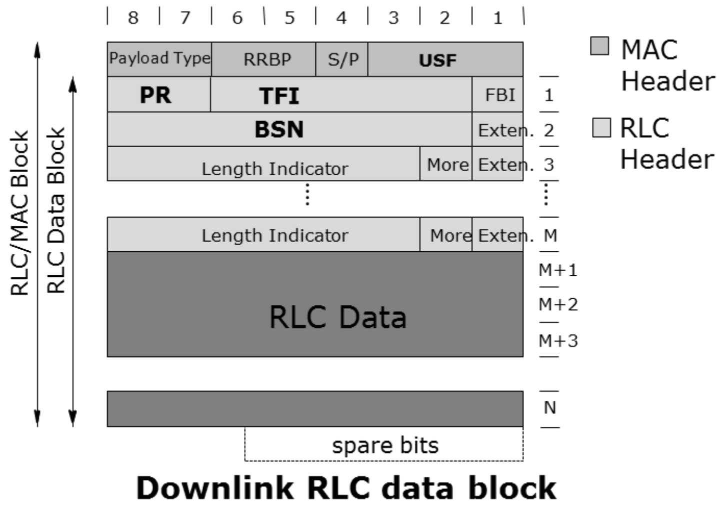


Figure 8: GPRS DL radio link control (RLC) data block

2.6 Random Access to a Control Channel on the PDCH

The GSM RACH is a request channel located by GSM 51-multi-frame at fixed positions in time on an UL slot. The GPRS packet random access channel (PRACH) is an UL control channel provided on both fixed and dynamically chosen positions of a PDCH. The RAB in GSM and GPRS has the same format and channel coding, with small differences in the meaning of the information carried.

The GSM RAB carries a random number used by the BS as a temporary MS address to assign it a bidirectional circuit-switched signaling channel for connection establishment, in response. In GPRS during association the random number is used like in GSM, but for establishing a virtual connection. In GPRS another random number is used by the BS during a Temporary Block Flow (TBF) as a temporary MS address to assign it on UL one Radio Block to communicate either its TLLI address and radio resource requirements (in two-phase access), or its address and packet data (one-phase access).

CELLPAC [14] describes the one-phase access of GPRS where the slot assigned by the BS may not be the next slot in time. The access protocol is DAMA of type (*Ui, Dei*) in both CELLPAC and GPRS.

A random access control channel dynamically provided on time positions of the packet dedicated TCH as used with GPRS was first introduced in [13] - [15].

2.7 UL State Flag (USF)

In [13] – [15] a CELLPAC TCH slot on UL, similar to DSMA and PRMA, is dynamically specified by the BS to be either used for random access by MSs assigned to that channel, or for UL packet data transmission by a given MS.

A Control Burst (CB) is transmitted on DL of the packet dedicated TCH providing the UL State Indication (USI) bit [15]. USI specifies whether the next UL time slot is reserved for random access (USI=0=FREE) by any MS or is reserved (USI=1). USF is a further developed USI.

The GPRS RLC/MAC block contains USF, see Figure 8. USF = FREE signals the next UL slot is reserved for random access. The other USF values address one out of seven MSs assigned to the PDCH to transmit its UL packet data in the next radio block.

USI and USF have in common that

- the next UL slot can be specified to be FREE for random access
- a value ‘not FREE’ reserves the next UL slot to the MS addressed.

With USF the MS is addressed by the USF value, in CELLPAC the MS is addressed by the MS-Random Number provided, together with USI. USI and MS-Random Number, together, cover all the functions of USF providing concurrent MSs reserved UL slots, whereby statistical multiplex transmission of UL packet traffic of MSs is enabled.

Dynamic placement of random access slots and reservation of next UL slot to MSs is controlled by USI. USI anticipates USF of GPRS PDCH.

2.8 Time Advance and Power Control for the Packet Channel

CELLPAC provides multiple MSs transmitting on the same PDCH with individual frame alignment (TA) and power control (PC) see Figure 7. Power Reduction (PR) is provided in the GPRS RLC/MAC block, Figure 8. Individual TA is provided by a GPRS control channel.

Both MS individual power control and frame alignment on the PDCH introduced by CELLPAC is used in GPRS.

2.9 Statistical Multiplex of MSs to the Dedicated Packet Channel

Different from circuit-switched data service known from GSM and other systems mentioned, GPRS provides MA of MSs to a PDCH for simultaneous packet data transmission in statistical multiplex on UL, see Figure 9. The PDCH is assigned for the duration of a small packet data segment instead of the duration of a voice talk-spurt or data burst as known from earlier systems. Simultaneous packet data transmission by statistical multiplex on UL is first introduced in [15].

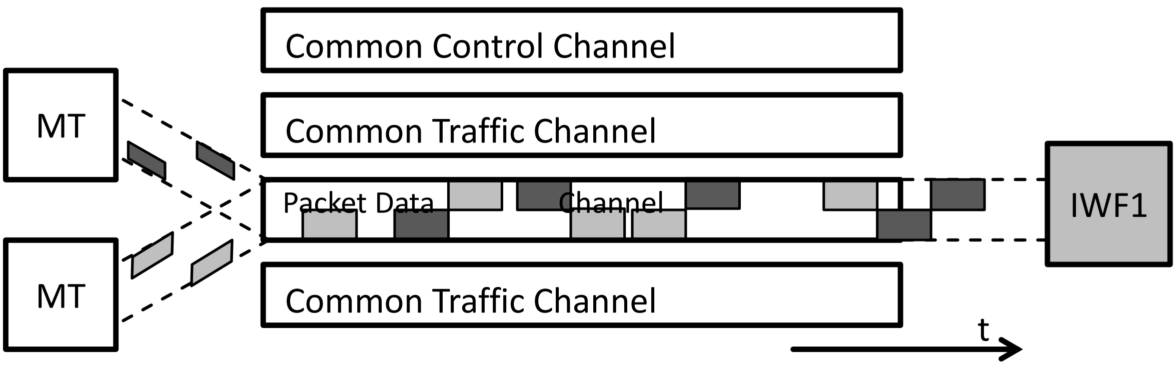


Figure 9: Multiplex transmission by two MSs on shared packet data channel

GPRS assigns the PDCH for data transfer in multiples of Radio Blocks (carrying four NBs). In [14] it is proposed to assign ≥4 NBs for data transfer of a MS.

Statistical multiplex of packet data of multiple MSs to a dedicated TCH was first introduced by CELLPAC.

2.10 Dynamic Placement of Control Channels

An ongoing transmission of a MS may be interrupted, like with GPRS by the BS by dynamically placing a PCCH CB on any DL slot informing by USI=0 all MSs that the next slot is reserved for random access [15]. An ongoing UL packet data transmission is interrupted thereby. In GPRS USF carried in DL RLC data block / RLC/MAC control block serves for the same purpose.

According to [25] more (dynamic) UL RA slots are required in DAMA protocols compared to DL control slots to efficiently solve access conflicts. PRMA (and DSMA) protocols are inflexible here. CELLPAC and GPRS controlled by USI and USF, respectively, are flexible to insert random access slots on UL when needed.

Dynamic placement of random access slots and possible interruption of UL data transfer was first introduced by CELLPAC and is used in GPRS.

2.11 Short Identifiers carried in Control and Data Channels

GPRS P-TMSI (derived from GSM TMSI) is represented in layer-2 by either TLLI (4byte derivative of P-TMSI) or TFI (5bit replacement of TLLI). User packet data transmitted on the RI in GPRS refer to the PDC via random numbers TLLI and TFI. In [13] datagrams are introduced to carry short addresses uniquely derived from GSM TMSI, corresponding to GPRS TLLI and TFI.

TLLI is an alias of the virtual connection identifier and is carried in RLC/MAC data blocks. USF is assigned to a MS having requested Temporary Block Flow (TBF) establishment for packet data transmission, and TFI is assigned to identify a specific TBF out of a number of TBFs that a MS may have active.

In CELLPAC MSs in in the request burst carry their virtual connection identifier, a concept first introduced in [9]. Alternately, a random number is proposed to be carried [14], [15] as used with GPRS, see Section 2.6.

Shortened MS identifiers carried in request packets are known from [9], [11], [15].

3. Similarities and differences of Packet Data Networks

In the following an attempt is made to compare concepts and implemented packet-switched networks described above. For that purpose the functions introduced as *GPRS Fundaments* are taken as comprehensive characterization whereby commonalities and differences of the various systems are identified resulting in Table 1. Only systems and concepts are considered known before CELLPAC was published.

	Packet-switching protocol Suite	*PS service in CS TDMA netwk.*	*DAMA proto-col type*	*Context establ. before data trx*	*Dynam. placement of UL/DL control on data chann*	*USF function*	*TA & PC for MSs sharing a TDMA channel*	*Statist.l Mux of MSs to TDMA chann.*	*>1 MS simult. Controlled*	*Short ID carried in ctrl. 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

Rows in Table 1 refer to the respective concepts / networks discussed in Sections 1 and 2. The DAMA protocol type shown in column three relates to packet data transfer (not to association of MSs to the network). Legends of columns refer to subsections of Section 2. Functions that do not apply (irrelevant or not specified) are represented as '-'. Functions that partly apply but are not worked out in sufficient detail in the respective system document are marked '0'. Functions that mostly apply are marked '(+)' and functions that fully apply are marked '+'.

Table 1 serves to visualize the extent GPRS *Fundaments* are present in concepts / networks known before GPRS was designed. The functions addressed in columns are mostly orthogonal to each other but are of different importance for GPRS. Therefore, it remains to the reader to derive its opinion on commonalities and differences of the systems discussed. In the author's view, first, similarities in the third column should be considered. Then the sum totals of 'plusses' per row should be evaluated and compared, giving good indication of the degree of similarities and differences of the systems. Clearly, CELLPAC matches GPRS by far at best.

4. History of GPRS: Ideas for 'Packet Radio' in GSM

In the early days of GSM around 1988, IBM and Motorola suggested to ETSI SMG that GSM should include packet mode data services, but this proposal was rejected [18] and no respective activity started. No earlier than in 1992, ETSI Special Mobile Group (SMG) created a Work Item '*Packet Radio*' for GSM.

At SMG1 meeting #3[2], August 1992 Stockholm/Sweden Ericsson stated in TDoc 221/92 they "*experience a strong and growing market interest for packet radio data with its inherent spectral efficiency*", and suggested "*to study packet data aiming for a high performance packet data service as an add-on to GSM*."

4.1 Research towards Cellular Packet Radio

In Europe mobile radio pre-competitive research towards 3G systems was funded 1988-1992 by the European Commission in a small three years project *RACE 1043 (Mobile Telecommunications)* from the *Research on Advanced Communications for Europe* program. The project was initiated and headed by Ed Candy of Philips. Its main outcome was a 'system framework' for UMTS [21] where the members of the project's System Group are

[2] ETSI SMG documents are available to members from http://docbox.etsi.org/zArchive/SMG/
http://ns2.quintillion.co.jp/3GPP/GSM/SMG_0x/Report/ (1≤x≤32) contains ETSI SMG TDocs 1992-2000.

named. John Dunlop of Strathclyde UK and J.M. DeVile [25] evaluated MA protocols in the project concluding PRMA [5] to be suited for UMTS if improved to handle potential access collisions. Mitrou [11] in a 1990 RACE 1043 paper introduced the MA protocol that in revised version is part of the UMTS standard. Clearly RACE 1043 was focusing 3G systems, not GPRS and this was continued in 1992 in RACE project 2066 (MONET).

In the U.S. sponsored by Federal Communications Commission fifteen wireless networks companies of U.S., Europe, and Japan cooperated in a 3G research project with Rutgers University WINLAB, NJ where the PRMA protocol [5] was developed besides others.

It appears reasonable that others may well have undertaken similar work but have been constrained from publishing it, for commercial or security reasons.

4.2 Involvement of ETSI SMG to specify GPRS

In 1993, ETSI SMG became responsible to specify GPRS. At that time, wireless Internet access was in its infancy and in GSM was only tentatively supported by circuit-switched data services. End of March 1993 (see TDoc SMG 200/93) a need was seen for extending the GSM "*suite of services to include a General Packet Radio Service (GPRS).*" This ETSI document seems to be the first where the term 'GPRS' was used to name the packet-data service in GSM. This document also specifies 'General Requirements' to be: "*Dynamically shared use of radio path by users generating 'bursty' packet traffic at different rates*." Authors of this document were aware of [14]. According to [18] it was a surprise to ETSI SMG when recognizing that it was possible to introduce packet radio into the existent GSM system. In June 1993 at ETSI SMG the Work Item 'Packet Radio' was added to the high priority list.

4.3 GPRS Standard Development

During 1993, more precise requirements and technical ideas for GPRS have been developed within ETSI SMG. In ETSI SMG1 TDoc 153/93, Clause 3.2.5, dated September 3, 1993, it is required that GPRS is "*implemented on a TCH*". SMG chairman said in [18]: "*It is only at SMG#6 (March 1993) that a process was started through which Phase 2+[3] would acquire its full dimension. It started with a document tabled by Nokia […] entitled 'GSM in a future competitive environment.' […]. I thought that what was needed was brain storming rather than quick decisions and suggested to hold an open workshop to which we could invite experts from non-ETSI companies.* "

Ali-Vehmas [19] writes in 2003: "*The GPRS standard development was started officially in the ETSI workshop 'GSM in a Future Competitive Environment', 12-13 October 1993 […]. There were two papers [15], [17] which both discussed the principles of the packet data over TDMA based radio system.*"

In [15] the advanced CELLPAC protocol is described and [17] describes a packet dedicated traffic channel which is accessed similar to the circuit-switched GSM data service, see Table 1. Authors of [15] were the only external experts invited to the workshop to present on '*Packet Radio'* in GSM.

GPRS slowly took shape first going into wrong directions, e.g., ETSI SMG1/SMG4 TDoc 235/93 states in Clause 3.2: „*If several mobiles are allocated simultaneously to the same Bm[4], Lm or SDCCH/8 channel, the TA function would not work. […] The conclusion is,*

[3] GSM Phase 2+ is the acronym for improvements to GSM Release '99, e.g. Packet Radio.

[4] Bm / Lm are full- / half-rate TCHs. SDCCH/8 is a bidirectional GSM control channel. TA is the MS specific time advance used for slot synchronization.

therefore, that only one mobile at any time may be allocated to a Bm, Lm or SDCCH/8 connection". But GPRS followed [15] and implemented statistical multiplex to a shared TCH.

4.4 Further Development of GPRS

In [18] it is said: "*In 1995 there were mainly debates about the functional principles and how such a concept should be integrated in existing GSM networks. The detailed work happened at ad-hoc meetings from SMG2 and SMG3. […]. Furthermore, a protocol stack discussion took place, because a protocol stack as now planned did not exist in classic GSM".*

ETSI SMG2 chairman Gunnar Sandegren coordinated GPRS standards development. To exemplify contributions by industry to SMG2 GPRS, examples are given in the sequel. Telia in TDoc 2/95 shows simulation results of the effectiveness of the *DSMA* protocol applied to GSM TCHs in terms of utilization, throughput, and access delay see also TDoc 95/94, but DSMA was not accepted in GPRS. Telia in TDoc GPRS 3/95 describes the architecture of GPRS access and core networks and related protocols with the steps of attachment of an MS, and the LLC and MAC protocols in detail. Ericsson in TDoc 4/95 underlines the importance of USF for the random access based packet reservation and in TDoc 6/95 introduces the PDCH 52-multiframe used in GPRS. Nokia in TDoc 35/94 proposes an improved multi-slot supporting MAC protocol *Variable Rate Reservation Access* (*VRRA)* originally proposed in TDocs 7/95, 18/95. Motorola in GPRS Ad-Hoc TDOC 11/95 reviews known MA protocols giving preference to the DSMA protocol. Ericsson in TDoc 143/96 introduces the RLC/MAC block formats (see Figure 8) and in TDoc 144/96 the RLC/MAC temporary block flow (TBF) procedures. Nortel compares in TDoc 96/102 the USF proposal against its proposed "allocation strategy". Siemens in TDoc 91/96G supports USF and TFI at PDCHs. All documents do not carry author names following ETSI rules. Clearly many unknown contributors have progressed GPRS to a mature system. Besides the example documents mentioned a large number of other TDocs exist proposing further improvements to the forthcoming GPRS standard.

Besides the *GPRS Fundaments* the GPRS standard comprises numerous refinements by many individuals, to enhance efficiency and flexibility of the service. It remains to the reader to decide whether or not to count this work as roots of GPRS.

Members of the author's research group continued cooperation with ETSI SMG analyzing various RI protocol proposals to result in publications [16] and [22], the former being the most cited GPRS paper today.

CELLPAC is the first system concept comprising the GPRS *Fundaments*. Some GPRS relevant functions were known earlier, as shown in Table 1. But it is the right combination of known and of new concepts that together constitute the *GPRS Fundaments*.

Three early patents related to GPRS radio-access [17], [23] and [24] were filed in 1993/94. Patent [24] most related to *GRPS Fundaments references* among others [13] as prior art; patent [23] filed before [24] gives reference to [14] and [15]. No IPR is known to the author covering the *GPRS Fundaments*.

5. Conclusions

GPRS replaced all other mobile packet data network technologies existent. Although introduced to the market since 2001 GPRS/EDGE is still the only omnipresent packet data service for mobile Internet access available on a global scale – like GSM. 3G and 4G mobile packet data services introduced by WCDMA, WiMAX, and LTE have patchy radio coverage in most regions only and mostly rely on 2.5G GPRS/EDGE to provide wider service coverage. The CELLPAC proposal anticipates the *GPRS Fundaments* introduced in Chapter 2 and describes how to introduce a packet-switching service to GSM.

Access to the Internet by wireless stations based on WLAN standard IEEE 802.11 is an important service but is limited to movable terminals with intermittent network connectivity, only. GPRS/EDGE was the break-through technology for mobile Internet access on a global scale. Evolved *GPRS Fundaments* can be found in 3G and 4G cellular radio systems. Accordingly, the CELLPAC authors may be also considered enablers of mobile Internet access. From the history of the GPRS standard development it appears that there are many unknown individuals having substantially contributed through their employer organizations. Therefore, this paper cannot claim to be complete in naming individuals having substantially contributed to GPRS. It remains to a history paper to be written to identify the roots of GSM layer-1 functions and related transceive technologies on top of which GPRS is running.

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