Chapter 1

Introduction

1.1. Background

Within our Information Society the Internet has become an important backbone for communication as well as for the distribution and access of information. The impressive growth of the Internet usage has partly been enabled by the increasing number of new services such as e-mail, World-Wide-Web (WWW) browsing, file transfer, streaming audio/video delivery, etc. The wide acceptance of the Internet has resulted in an exponential growth of packet data traffic load. In order to meet these changing traffic patterns, more and more network operators adapt their strategies and plan to migrate to IP-based backbone networks. Clearly, the Internet will dominate our daily life in the future much more than today.

Meanwhile, mobile networks face a similar trend of exponential traffic increase and growing importance to users. With almost eight hundred million cellular subscribers worldwide [1], users have overwhelmingly embraced the concept of having a telephone that is always with them. In some countries, such as Finland, the number of mobile subscriptions has already exceeded the number of fixed lines.

The combination of both developments, the growth of the Internet and the success of mobile networks, suggests that the next trend will be an increasing demand for mobile access to Internet applications. The current success of the *iMode* mobile data service offered by the operator NTTDoCoMo in Japan, with more than 26 million users in two and a half years [2], is a good milestone for forecasting that within the next few years there will be an extensive demand for wireless data services, especially wireless Internet.

Nevertheless, mobile telecommunication networks, such as the Global System for Mobile communications (GSM) [3], have been designed primarily for voice communications and are based on circuit switched radio transmission, which reserves traffic channels for entire communication time. Therefore, when data traffic has bursty behavior (typical Internet applications show such traffic behavior), circuit switching results in a highly inefficient utilization of radio resources, and the service is too expensive for most users, as the users must pay for the whole connection time even for idle periods when no data is sent. Moreover, data rates are too slow and the connection setup takes too long and is rather complicated.

In order to address the inefficiencies of circuit switched mobile networks for transporting data traffic, packet switching techniques have emerged in wireless networks. Unlike circuit switching, in packet switching a traffic channel will be only allocated when needed and will be released immediatly after the transmission of packets. With this principle, multiple users can share one physical channel (statistical multiplexing), resulting in a much better utilization of the radio resources. Two cellular packet data technologies have been developed so far: Cellular Digital Packet Data (CDPD) (for AMPS, IS-95 and IS-136) [4] and the General Packet Radio Service (GPRS) (for GSM), which is the field of this Thesis.

GPRS is a new bearer service for GSM that greatly improves and simplifies wireless access to packet data networks (PDNs), e.g., to the Internet. It uses packet switching principles to transfer data packets in an efficient way between mobile stations (MS) supporting GPRS and external PDNs. Users of GPRS benefit from shorter access times, higher data rates and an optimized usage of radio resources. In addition, GPRS enables volume based charging in contrast to time-oriented charging applied for GSM. Thus, billing can be based on the amount of transmitted data, then you can stay constantly on-line while you pay only for the occasional data transfer, resulting in a cheaper communication cost.

Since the GPRS is to be integrated into the GSM infrastructure, both services must share the same radio resources. In the ETSI standard GSM 03.64 [5], principles are described how to allocate radio resources in a fixed manner or dynamically for GPRS according to the "capacity on demand" principle. Details that are related to certain channel allocation strategies are left open and are implementation-specific, so the choice of the GPRS/GSM radio resource allocation algorithm is critical to the performance of both systems.

In existing literature related to radio resource management in overlaid GPRS/GSM networks, three different radio resource allocation techniques can be found:

1. Complete Partitioning (CP): full partitioning of radio resources between GPRS and GSM, where some channels are reserved for GPRS service only and the others are exclusively used by GSM circuit switched services.
2. Complete Sharing (CS): full sharing of radio resources between GPRS and GSM, where all channels are shared between both services.

3. Partial Sharing (PS): some channels are reserved for GPRS service only and the others are shared between both services.

Several studies on GPRS performance in literature show that the combination of shared and dedicated traffic channels -*PS technique*- provides enhanced performance for GPRS and offers an effective GPRS service that can meet different quality of service (QoS) requirements for the data users. This PS approach is best able to adapt to the performance profile suggested over a range of offered traffic loads, so mobile operators should employ it in order to allow the system to function flexibly.

1.2. The problem

Ideally a GSM operator would like to retain the same GSM grade of service (GoS) and QoS when GPRS is introduced. However, there are several reasons that make necessary reserving some channels exclusively for GPRS in order to guarantee the QoS of the GPRS services:

- As the introduction of HSCSD service [6] into the GSM system, it might be difficult to guarantee the QoS of GPRS if no channel is dedicated to GPRS.
- As the GPRS traffic load increases, some minimum number of traffic channels should be always reserved for GPRS to guarantee some minimum service level.
- As multiple classes of QoS and multiple classes of users are supported in GPRS, it might be difficult to ensure the GPRS performance if no channel is dedicated to GPRS.
- As said in section 1.1, the resource allocation technique that provides better performance is the PS, so dedicated channels are necessary to have an effective GPRS service.

It is obvious that if exclusive reservation of channels for GPRS is carried out by the GSM operator, such reservation will reduce the number of channels available for existing GSM services and, hence, reduce their capacity. Furthermore, the introduction of GPRS into the GSM network without allocating new spectrum will increase the interference probability of circuit switched services and, hence, reduce also the quality of GSM services [7]. It is a network planning problem to guarantee the GoS and QoS of the existing GSM circuit switched services when overlaying GPRS onto the GSM network. This generates a research problem to estimate the effects of GPRS on the quality and capacity of existing GSM services.

Within the existing GSM circuit switched services, it is necessary to consider the difference between calls that are initiated in the cell and calls that are handed over from other cells. The reason is that traffic that is handed over is usually treated with a higher priority than originating calls, because forced termination of a call in progress is clearly less desirable than blocking a new call attempt. As a result, various handover priority-based channel allocation schemes have been proposed by many researchers in the past, which can be used for counteracting the reduction of capacity of GSM services due to GPRS implementation at the same time that prioritize handover traffic over new call attempts. In general, these handover prioritization schemes result in a decrease in handover failures, at the expense of some increase in call blocking and decrease in the ratio of carried to offered traffic.

The problem to be solved is how to keep up with the quality demands of new GPRS data services when simultaneously ensuring the quality of existing ones, and at the same time prioritize handover requests over new call attempts in order to protect ongoing calls from forced termination.

1.3. Objectives

The main task of this Thesis is to find out how much resources can be assigned to GPRS traffic and how this assignment affects the existing GSM services, mainly focusing on the impacts on the capacity of handover traffic. The main objective is to improve perceived quality of handover service by minimizing the probability of forced termination of ongoing calls due to handover failures. Throughout this research, we will understand how the existing GSM services are affected by GPRS due to the need of guaranteing some QoS of GPRS service, and which parameters need to be taken into consideration when the operators assign network resources for GPRS.

The main performance criteria of interest in this Thesis are: probability of handover failure, probability of new call blocking, carried versus offered traffic, channel utilization and GPRS performance (e.g. throughput, delay, etc). The teletraffic performance of an overlaid GPRS/GSM network employing different handover prioritization policies is evaluated by simulations under a wide range of load situations as well as different percentages of GPRS users.

1.4. Means and methodology

The study requires is to implement a simulation program and perform simulations to estimate the optimal radio resource allocation strategy and handover prioritization scheme in order to allow the overlaid system to adjust flexibly to an expected growing GPRS traffic load when simultaneously ensuring the existing services.

To illustrate a more practical approach, the simulation is focused only on one cell of the cellular mobile system, whose behavior is isolated from those of the other cells, that are collectively described only through the handover requests toward the investigated cell. The effects of an estimated GPRS traffic load increase on capacity of handovers and new calls are computed on the cell. Thereafter, the teletraffic performance of different handover prioritization schemes is evaluated and compared with the non-prioritized scheme, and conclusions are drawn. Considering the level of complexity of the real cellular problem, some assumptions are made, especially regarding the distributions of certain random quantities.

The results of this research can be used to generate efficient radio resource management algorithms and can provide useful guidelines for radio network planning under GPRS and GSM traffic assumption.

1.5. Contents of the Thesis

The Thesis is divided into seven chapters. A concise introduction to the subject of the Thesis has been given in this chapter. In chapter 2, a brief overview of the GSM system is done and the key concepts of GPRS are explained. It is assumed that the reader is familiar with the basic concepts of cellular networks. In chapter 3, the principles of radio resource management for GPRS are discussed and different radio resource allocation techniques in overlaid GPRS/GSM networks are studied. In chapter 4, a detailed performance study of the GPRS service is presented based on several studies found in literature. In chapter 5, the impacts caused by the GPRS implementation on the existing GSM services are discussed, especially the impact on handover traffic, and several ways of counteracting these impacts are proposed. Different handover prioritization schemes are presented. In chapter 6, a simplified case study of an overlaid GPRS/GSM cell is analyzed using an event-oriented simulator; simulation results are summarized and discussed and conclusions are drawn. Finally, some useful guidelines for GPRS/GSM network planning are given in chapter 7.

1.6. Related work

Lindemann and Thümmler have recently investigated how many channels should be allocated permanently for GPRS under a given amount of traffic in order to guarantee appropriate QoS for the GPRS service [8]. The goal of this Thesis is to study how this number of channels reserved for GPRS impacts on capacity of existing GSM services, mainly focusing on the impact on handover traffic. Our contribution is to investigate the effectiveness of different handover priority-based channel allocation schemes on increasing the system capacity for handovers and, thus, improving the handover performance. A previous knowledge about different GPRS implementation strategies in existing GSM networks and their performance is necessary in order to make an efficient use of the scarce available spectrum. Therefore, chapter 4 contains a detailed survey with existing material about the performance of the GPRS service, where all the consulted documents are properly referenced.

Chapter 2

General Packet Radio Service (GPRS)

In this chapter a brief overview of the GSM system is done and the key concepts of the GPRS service are explained based on references [9], [10] and [11]. More information of the GPRS system can be found in the web page of the European Telecommunications Standards Institute (ETSI) [12], where all the GPRS standards are available on-line.

2.1. Background on GSM

In order to understand the GPRS system, it is necessary to have a broad understanding of GSM. A brief overview of GSM is given here, while general description can be found in [3].

2.1.1. GSM concepts and services

The GSM is the pan-European digital cellular system standardized by ETSI. Two frequency bands are reserved for GSM operation, one for the uplink (890-915MHz) and one for the downlink (935-960MHz). In addition to cellular operation in the 900MHz band, the 1800MHz and 1900MHz bands are also used to allow more GSM operators. Each of these bands is divided into single carrier channels of 200 kHz width. GSM employs a time division multiple access (TDMA) scheme on each frequency channel, dividing it into 8 timeslots. Blocks of 8 timeslots are grouped to form a TDMA frame. Frames, in turn, are grouped into multiframes, superframes and hyperframes.

GSM is a circuit switched oriented system primarily designed for voice services (telephony), but where data transmission services are also available. The basic GSM data services are:

- Short message service (SMS), which is a data service that allows the delivery of text messages of up to 160 characters from/to MSs. It is optimized to short messages and notifications.
- GSM circuit switched data service, which enables a maximum data rate of 9,6 Kbit/s (e.g. facsimile).

2.1.2. GSM system architecture

Figure 2.1 shows the system architecture of a GSM public land mobile network (PLMN) with essential components [3]. The area covered by a GSM network is divided into a number of cells, each served by its own base transceiver station (BTS). Several BTSs together are controlled by one base station controller (BSC). The combined traffic of the MSs in their respective cells is routed through a switch, the mobile switching center (MSC). Connections originating from or terminating in the fixed network are handled by a dedicated gateway mobile switching center (GMSC). Through the GMSC, the GSM system communicates with other networks such as the public switched telephone network (PSTN), integrated services digital network (ISDN), circuit-switched public data network (CSPDN) and packet-switched public data network (PSPDN). GSM networks are structured hierarchically. They consist of at least one administrative region, which is assigned to a MSC. Each administrative region is made up of at least one location area (LA). A location area consists of several cell groups. Each cell group is assigned to a BSC.

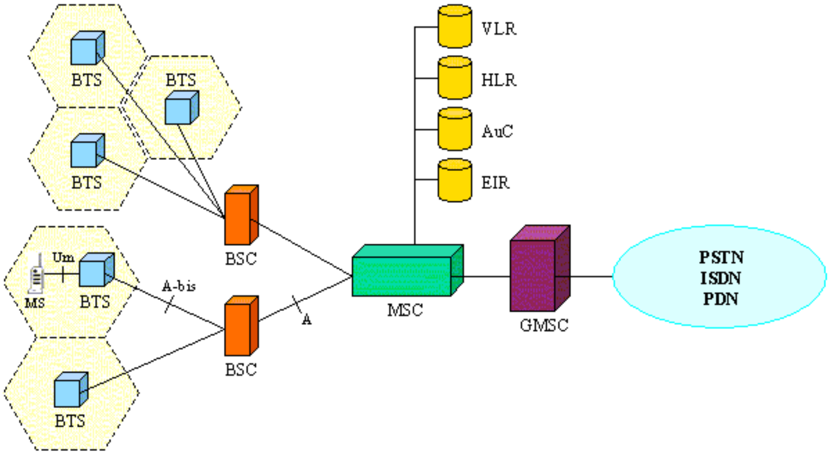


Figure 2.1. GSM system architecture with essential components

GSM defines a number of network databases that are used in performing the functions of network management and call control: the home location register (HLR), the visitor location register (VLR), the authentication center (AuC) and the equipment identity register (EIR). The HLR maintains and updates the mobile subscriber’s location and his/her service profile information. The VLR maintains the same information locally, when the subscriber is roaming. The AuC generates and stores security-related data such as keys used for authentication and encryption. The EIR is used to list the subscribers’ equipment identities, which are used for identification of unauthorized subscriber equipment, and hence denial of service by the network.

2.1.3. GSM evolution

Technology creation for GSM has proceeded in three phases. The technology standardized in *phase 1* was sufficient for the introduction of commercial GSM services, including telephony, SMS and facsimile, in 1992. In 1996, *phase 2* completed the original GSM design task and established a framework for ongoing technology enhancement. GSM standardization is now in *phase 2+*, which consists of a large number of projects including improved speech coding and advanced data transmission services. Three new data services are HSCSD, EDGE and GPRS, which is the subject of this Thesis.

- HSCSD [6], which stands for high speed circuit switched data, extends the basic GSM circuit switched data service to higher data rates up to 115kbit/s by both using multiple channels for data transfer (multi-slot operation) and introducing new channel coding schemes. This service is the best bearer for real-time services, like video conferencing. In spite of the fact that HSCSD requires minimum new infrastructure, GSM operators are putting all their effort towards GPRS.
- EDGE [13], which stands for enhanced data rates for GSM evolution, enhances both HSCSD and GPRS by using new modulations in order to provide even higher data rates (it will triple the data rates available with GPRS and HSCSD). It is already considered by the operators as a third generation (3G) technology.

2.2. GPRS concepts

As impressively demonstrated by the Internet, packet switched networks make more efficient use of the resources than circuit switched ones for bursty data applications, such as Internet services, and provide more flexibility in general; the transmission medium is used on demands only and, with statistical multiplexing, one physical channel can be shared by many users. GPRS is a packet switched extension of GSM which efficiently accommodates these data sources that are bursty in nature. It is introduced in order to provide more efficient access to PDNs from cellular networks compared to existing circuit switched services provided by GSM. GPRS supports the world's leading internet communication protocols, the Internet protocol (IP) and X.25, as well as the connectionless network protocol (CLNP) and the connection-oriented network protocol (CONP).

The most important advantage of GPRS is the possibility of charging based on traffic volume. In circuit switched services, billing is based on the duration of the connection; this is unsuitable for applications with bursty traffic, because users must pay for the entire airtime, even for idle periods when no packets are sent (e.g., when the user reads a web page). However, billing based on the amount of transmitted data makes cost-effective to remain constantly connected, because it allows that users can be on-line over a long period of time but they are billed based on the transmitted data volume, resulting in a cheaper cost.

The channel allocation in GPRS is different from the original allocation scheme of GSM. On the one hand, GPRS allows a single MS to transmit on multiple timeslots of the same TDMA frame (multi-slot operation). This results in a very flexible channel allocation: one to eight timeslots per TDMA frame can be allocated to one MS. On the other hand, a timeslot can be assigned temporarily to an MS, so that one to eight MSs can use one timeslot (statistical multiplexing). Moreover, uplink and downlink channels are allocated separately, which efficiently supports asymmetric data traffic.

2.3. GPRS system architecture and fundamental functionality

The existing GSM network does not provide adequate functionality to support packet data routing and transfer. Therefore, the conventional GSM structure has been extended by a new class of logical network nodes in order to create an end-to-end packet transfer mode: the *GPRS support node* (GSN). GSNs are responsible for the delivery and routing of data packets between the MSs and the external PDNs. Figure 2.2 illustrates the GPRS system architecture.

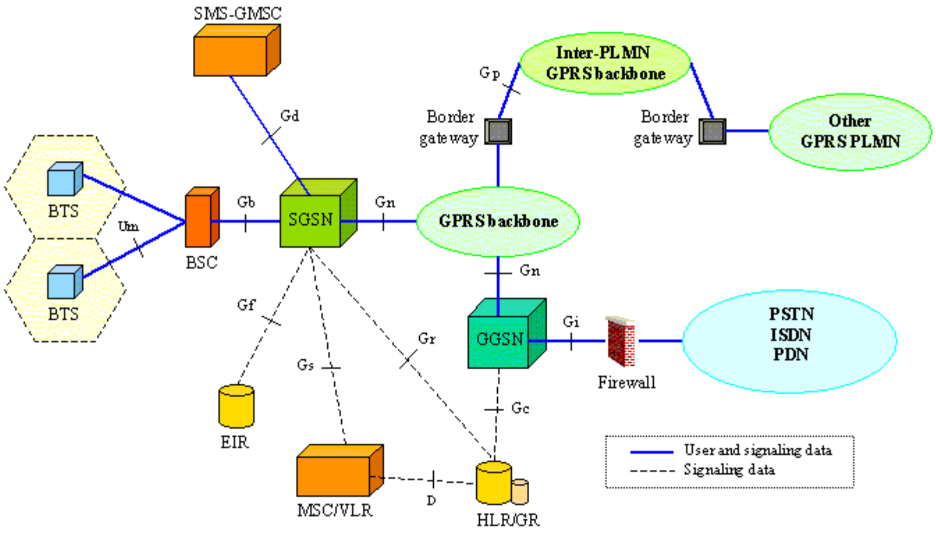


Figure 2.2. GPRS system architecture

The *serving GSN* (SGSN) is responsible for the delivery of packets from/to the MSs within its service area. Its tasks include packet routing and transfer, mobility management, logical link management, and authentication and charging functions. All GPRS user-related data needed by the SGSN to perform these tasks is stored within the *GPRS register* (GR), which is conceptually part of the GSM HLR. The GR stores the user profile, the current SGSN address and the PDN protocol (PDP) address(es) for each GPRS user in the PLMN.

The *gateway GSN* (GGSN) acts as a logical interface between the GPRS backbone network and the external PDNs. It converts the GPRS packets coming from the SGSN into the appropriate PDP format (e.g., IP or X.25) and sends them out on the corresponding PDN. In the other direction, PDP adresses of incoming data packets are converted to the GSM address of the destination user, and then the packets are sent to the responsible SGSN. For this purpose, the GGSN stores the current SGSN address of the user and his or her profile by interrogation from the HLR/GR. *Firewalls* are used between the GGSN and external PDNs to provide security.

In general, there is a many-to-many relationship between the SGSNs and the GGSNs: a GGSN is the interface to external PDNs for several SGSNs; an SGSN may route its packets over different GGSNs to reach different PDNs. All GSNs are connected via an IP-based GPRS backbone network. There are two kinds of GPRS backbones:

- *Intra-PLMN IP backbone networks* connect GSNs of the same PLMN and are therefore private IP-based networks of the GPRS network provider.
- *Inter-PLMN IP backbone networks* connect GSNs of different PLMNs. A roaming agreement between two GPRS network providers is necessary to install such a backbone, and *border gateways* (BG) are installed between each PLMN to provide roaming between networks.

2.4. GPRS service characteristics

2.4.1. Applications for GPRS

GPRS is standardized to optimally support a wide range of applications ranging from very frequent transmissions of small data volumes to infrequent transmissions of medium to large data volumes. Beyond all doubt, the most important application for GPRS is *wireless Internet*. Wireless PCs should support any conventional Internet-based application, like file transfer, e-mail, chat or web browsing. 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. Based on this standardization effort, even transmission of video information seems to be applicable for GPRS.

Another very important application area is represented by road traffic and transport informatics (RTTI) applications, such as distribution of traffic control information (road and weather conditions), fleet management, route guidance and parking management. Other possible applications are connected to financial transactions: electronic cash and fund transfers do not have very high communication requirements, and GPRS could be used as a bearer for these applications as well. Applications like notification of alarms, collection of sensor values, delivery of statistics, home automation, access to databases, surveillance systems, lottery transactions, etc are also possible by equipping various electronic devices, either static or mobile, with a GSM/GPRS transceiver.

2.4.2. Service description

The bearer services of GPRS offer end-to-end packet switched data transfer between two MSs or between an MS and various terminals, attached to either the GPRS network or the external PDN. There are two different kinds of services: the point-to-point (PTP) service and the point-to-multipoint (PTM) service. The *PTP service* offers transfer of data packets between two users. It is offered in both connectionless mode and connection-oriented mode. The first type is a datagram-like service, intended to support bursty noninteractive applications based on the IP or the CLNP. The second type is intended to support bursty transactional or interactive applications based on X.25 or the CONP. The *PTM service* offers transfer of data packets from one user to multiple users. The functionality of the PTM service center (PTM-SC) to handle the PTM service is included within the GGSN. There exist two kinds of PTM services:

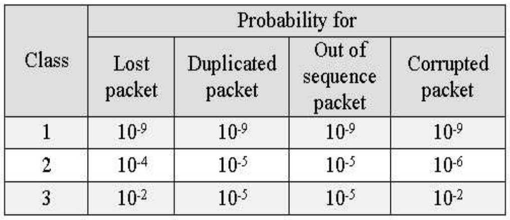
- Using the multicast service (PTM-M), data packets are broadcast to all subscribers in a certain geographical area. A group identifier indicates whether the packets are intended for all users or only a subset belonging to a specific PTM group.
- Using the group call service (PTM-G), data packets are addressed to a predefined group of users controlled by a multicast server and are sent out in the geographical areas where the group members are currently located.

It is also possible to send SMS messages over GPRS by connecting the GSM SMS-MSC to the SGSN.

2.4.3. Quality of service

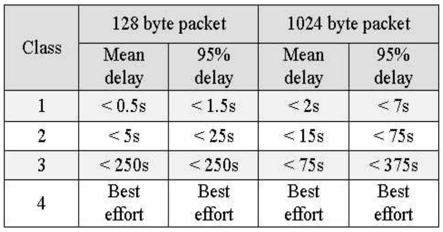
The QoS requirements of typical mobile packet data applications are very diverse (e.g., consider real-time multimedia, web browsing and e-mail transfer). Support of different QoS classes, which can be specified for each individual session, is therefore an important feature. GPRS allows defining QoS profiles using the parameters service precedence, reliability, delay and throughput.

- The *service precedence* is the priority of a service in relation to another service. There exist three levels of priority: high, normal and low.
- The *reliability* indicates the transmission characteristics required by an application. Three reliability classes are defined, which guarantee certain maximum values for the probability of loss, duplication, mis-sequencing and corruption of packets (table 2.1).
- The *delay* parameters define maximum values for the mean delay and the 95-percentile delay (table 2.2). The delay is defined as the end-to-end transfer time between two communicating MSs or between an MS and an external PDN. This includes all delays within the GPRS network, e.g., the delay for request and assignment of radio resources (access delay), the data message transmission time (transfer delay) and the transit delay in the GPRS backbone network. The 95-percentile delay is the maximum delay guaranteed in 95 percent of all transfers.
- The *throughput* specifies the user requested data rate. It is defined by two negotiable parameters, the maximum/peak bit rate and the mean bit rate.



Class	Probability for			
	Lost packet	Duplicated packet	Out of sequence packet	Corrupted packet
1	10^{-9}	10^{-9}	10^{-9}	10^{-9}
2	10^{-4}	10^{-5}	10^{-5}	10^{-6}
3	10^{-2}	10^{-5}	10^{-5}	10^{-2}

Table 2.1. Reliability classes



Class	128 byte packet		1024 byte packet	
	Mean delay	95% delay	Mean delay	95% delay
1	< 0.5s	< 1.5s	< 2s	< 7s
2	< 5s	< 25s	< 15s	< 75s
3	< 250s	< 250s	< 75s	< 375s
4	Best effort	Best effort	Best effort	Best effort

Table 2.2. Delay classes

Throughput can be negotiated, while delay, reliability and service precedence are classified by different QoS classes. Using these QoS classes, QoS profiles can be negotiated between the mobile user and the network for each session, depending on the QoS demand and the current available resources. The billing of the service is then based on subscription fees paid regularly for a fixed period and traffic fees paid as a function of data volume, type of service requested and the chosen QoS profile.

2.4.4. Simultaneous usage of GSM and GPRS services

In a GPRS/GSM network, conventional GSM circuit switched services (speech, circuit data and SMS) and GPRS packet switched services can be used in parallel. In order to serve the different needs of various market segments, three MS classes are defined, each with distinct capabilities:

- A *class A* mobile station supports simultaneous operation of GPRS and conventional GSM services.
- A *class B* mobile station is able to register with the network for both GPRS and conventional GSM services simultaneously. In contrast to an MS of class A, it can only use one of the two services at a given time.
- A *class C* mobile station can attach for either GPRS or conventional GSM services. Simultaneous registration (and usage) is not possible. An exception are SMS messages, which can be received and sent at any time. This MS class is matched to the low-cost requirement of the mass market.

2.5. Session management, mobility management and routing in GPRS

2.5.1. Session management

Before an MS can use GPRS services, it must register with an SGSN of the GPRS network. The network checks if the user is authorized, copies the user profile from the HLR/GR to the SGSN, and assigns a packet temporary mobile subscriber identity (P-TMSI) to the user. This procedure is called **GPRS attach**. For MSs using both circuit and packet switched services it is possible to perform combined GPRS/IMSI attach procedures. The disconnection from the GPRS network is called **GPRS detach**. It can be initiated by the MS or by the network.

To exchange data packets with external PDNs after a successful GPRS attach, an MS must apply for one or more addresses used in the PDN, e.g., for an IP address in case the PDN is an IP network. This address is called PDP address. For each session, a so-called *PDP context* is created, which describes the characteristics of the session. It contains the PDP type (e.g., IPv4), the PDP address assigned to the MS (e.g., IP address -129.187.222.10-), the requested QoS and the address of a GGSN that serves as the access point to the PDN. This PDP context is stored in the MS, the SGSN and the GGSN. With an active PDP context, the MS is “visible” for the external PDN and is able to send and receive data packets. The mapping between the two addresses PDP and IMSI, enables the GGSN to transfer data packets between PDN and MS. A user may have several simultaneous PDP contexts active at a given time (multiple parallel sessions -up to 11-). The HLR/GR keeps these PDP contexts for each MS as part of the subscription data.

2.5.2. Mobility management

During the GPRS session, the location of an MS is tracked according to the three-state model shown in figure 2.3. In “*idle state*”, the MS is not reachable. Performing a GPRS attach, the MS gets into “*ready state*”. With a GPRS detach it may disconnect from the network and fall back to “idle state”. The “*standby state*” will be reached when an MS does not send any packets for a long period of time, and therefore the ready timer (which was started at GPRS attach) expires.

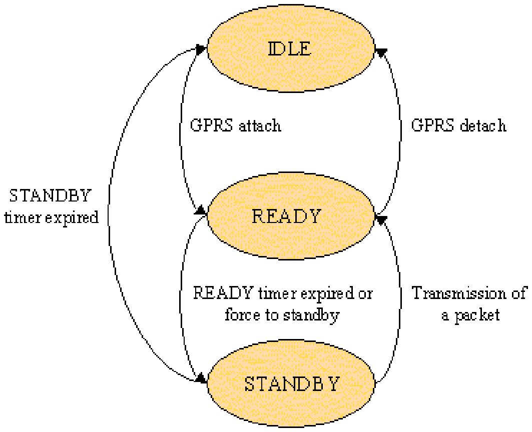


Figure 2.3. State model of a GPRS mobile station

There are no handovers between cells in GPRS; the cell is selected autonomously by the MS and the reselection parameters are sent from the network. The location update frequency is dependent on the state of the MS. In “idle state”, no location updating is performed, i.e., the current location of the MS is unknown to the network. An MS in “ready state” informs its SGSN of every movement to a new cell. In “standby state”, the location information is updated only when the routing area (RA) is changed. This RA is a subset of the GSM LA and consists of an operator-defined group of cells. The SGSN will only be informed when an MS moves to a new RA; cell changes will not be disclosed. To find out the current cell of an MS in “standby state”, paging of the MS within a certain RA must be performed. For MSs in “ready state”, no paging is necessary.

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-

SGSN 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 HLR/GR since the routing context has no change. If the old RA is served by another SGSN, this new SGSN inquires the old SGSN to send the PDP context/s of the MS. Afterwards, GGSN and HLR/GR are informed about the new routing context, and the PDP context/s are removed by the old SGSN.

2.5.3. Routing

An example of how packets are routed in GPRS is presented in figure 2.4. It is assumed that the PDN is an IP network and that the home-PLMN of the GPRS MS is PLMN2. It is also assumed that an IP address has been assigned to the MS by the GGSN of PLMN2 or PLMN1.

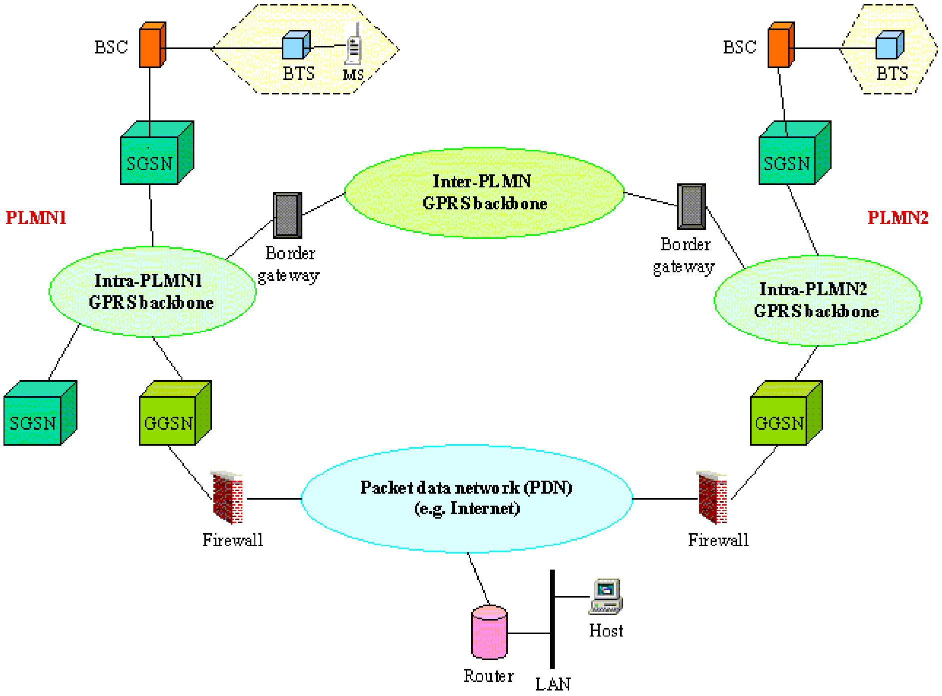


Figure 2.4. GPRS routing example

The GPRS MS located in PLMN1 sends packets to a host connected to the IP network, e.g., to a server connected to the Internet. The SGSN that the MS is registered with encapsulates the packets from the MS, examines the PDP context and routes them through the intra-PLMN1 GPRS backbone to the appropiate GGSN. The GGSN decapsulates the packets and sends them out on the IP network (Internet), where specific routing procedures are applied to send the packets to the corresponding host.

The host is now sending packets to the MS. The packets are sent out onto the IP network and are routed to the GGSN of PLMN2 (the home-GGSN of the MS). The GGSN queries the HLR/GR and obtains the information that the MS is currently located in PLMN1. It encapsulates the incoming packets and tunnels them through the inter-PLMN GPRS backbone to the appropriate SGSN in PLMN1. The SGSN decapsulates the packets and delivers them to the MS.

2.6. GPRS protocol architecture

Figure 2.5 illustrates the protocol architecture of the GPRS transmission plane up to the network layer according to the international organization for standardization / open systems interconnection (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.

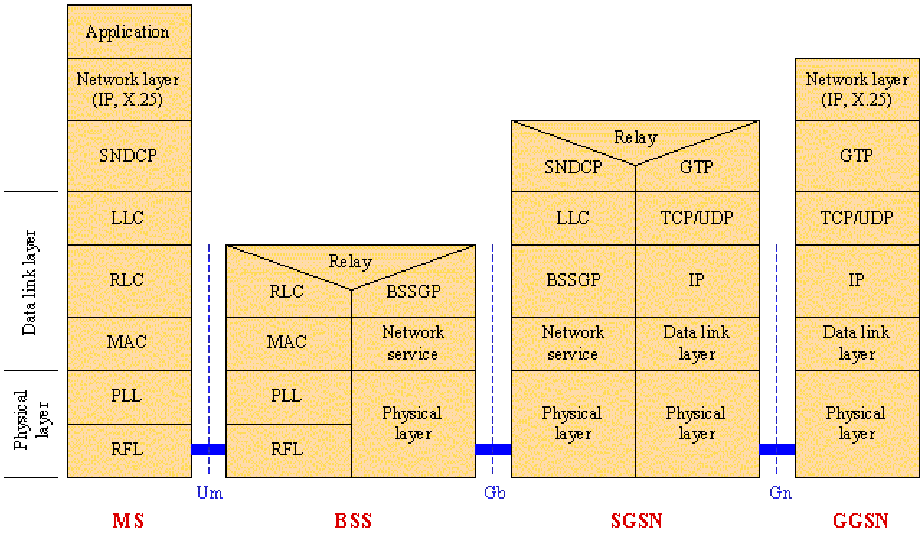


Figure 2.5. Protocol architecture of the GPRS transmission plane

Between two GSNs, the *GPRS tunnel protocol* (GTP) tunnels the protocol data units (PDU) through the GPRS backbone network by adding routing information. GTP packets carry the user’s IP or X.25 packets. Below GTP, the transmission control protocol (TCP) or user datagram protocol (UDP) and the IP are employed to transport the GTP packets within the GPRS backbone network. Depending on the operator’s network architecture, Ethernet cabling, ISDN links or asynchronous transfer mode (ATM)-based protocols may be used below IP.

Between the SGSN and MS, the *subnetwork dependent convergence protocol* (SNDCP) maps network-level protocol characteristics onto the underlying logical link control and provides multiplexing of multiple network-layer messages onto a single virtual logical link connection. Furthermore, ciphering, segmentation and compression functionality are covered by SNDCP. Between the BSS and SGSN, the *BSS GPRS protocol* (BSSGP) conveys routing and QoS-related information, and operates above frame relay (FR).

Radio communication between an MS and the GPRS network covers physical and data link layer functionality. The data link layer has been separated into two distinct sublayers: the *logical link control* (LLC) and *radio link control/medium access control* (RLC/MAC) sublayers. The LLC layer operates above the RLC/MAC layer and provides a highly reliable logical link between the MS and its assigned SGSN. To allow introduction of alternative radio solutions without major changes, it is independent of the RLC/MAC protocol as far as possible. Both acknowledged and unacknowledged data transmission modes are supported. Protocol functionality is based on LAPDm used within the GSM signaling plane, but with support for PTM transmission. According to common terminology, the protocol is called LAPG.

The RLC/MAC layer provides services for information transfer over the physical layer of the GPRS radio interface. It defines the procedures that enable multiple MSs to share a common transmission medium which may consist of several physical channels. The RLC layer is responsible for the transmission of data blocks across the air interface and the backward error correction (BEC) procedures consisting of selective retransmission of uncorrectable blocks (ARQ, automatic repeat request). The MAC layer itself is derived from a slotted Aloha protocol and operates between the MS and BTS. It is responsible for access signaling procedures for the radio channel governing the attempts to access the channel by the MSs, and the control of that access by the network side. It performs contention resolution between channel access attempts, arbitration between multiple service requests from different MSs and medium allocation to individual users in response to service requests.

The physical layer between MS and BSS is split up into a *physical link sublayer* (PLL) and *a physical RF sublayer* (RFL). The PLL provides services for information transfer over a physical channel between the MS and the BSS. These functions include data unit framing, data coding, and the detection and correction of physical medium transmission errors. The RFL conforms to the GSM 05 series of 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.

2.7. GPRS radio interface

The GPRS radio interface protocol is concerned with communications between the MS and BSS at the physical, MAC and RLC protocol layers. When a GSM operator decides to offer GPRS-based services within a cell, one or several physical channels from the common pool of available channels may be allocated to packet transfer. The principles of radio resource management and multiple access in GPRS are described in chapter 3.

2.7.1. Logical channels

On top of the physical channels, a series of logical channels are defined to perform a multiplicity of functions, e.g., signaling, broadcast of system information, synchronization, channel assignment, paging or payload transport. A physical channel dedicated to packet data transfer is called packet data channel (PDCH). As with conventional GSM, the PDCHs can be divided into two categories: traffic channels and signaling/control channels.

The *packet data traffic channel* (PDTCH) is employed for the transfer of user data. One MS can use several PDTCHs simultaneously (multi-slot operation) for individual packet transfers. The *packet broadcast control channel* (PBCCH) is a unidirectional point-to-multipoint signaling channel from the BSS to the MSs. It is used by the BSS to broadcast GPRS system specific information to all GPRS terminals in a cell. Besides system information about GPRS, the PBCCH should also broadcast important system information about circuit switched services, so that a GSM/GPRS terminal does not need to listen to the broadcast control channel (BCCH).

The *packet common control channel* (PCCCH) is a bidirectional point-to-multipoint signaling channel that transports signaling information for network access management, e.g., for allocation of radio resources and paging. It consists of four sub-channels:

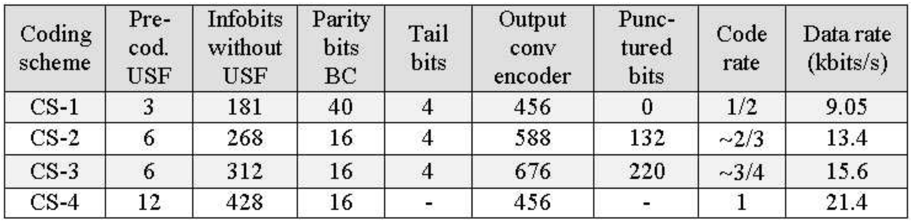
- The packet random access channel (PRACH) is used by the MSs to initiate uplink packet transfer and respond to paging messages. It is used in uplink direction only.
- The packet access grant channel (PAGCH) is used only on the downlink to send resource assignment information to an MS prior to the packet transfer.

- The packet paging channel (PPCH) is used by the BSS to find out the location of an MS prior to downlink packet transfer. It is used in downlink direction only.
- The packet notification channel (PNCH) is used to send a PTM notification to a group of MSs prior to a PTM packet transfer. The notification has the form of a resource assignment for the packet transfer. It is also used in downlink direction only.

The *packet dedicated control channel* is a bidirectional point-to-point signaling channel. It contains the channels PACCH and PTCCH:

- The packet associated control channel (PACCH) is always allocated in combination with one or more PDTCH that are assigned to one MS. It transports signaling information related to one specific MS (e.g., power control information, acknowledgements).
- The packet timing advance control channel (PTCCH) is used for adaptative frame synchronization.

The coordination between circuit switched and packet switched logical channels is important. If the PCCCH is not available in a cell, an MS can use the common control channel (CCCH) of conventional GSM to initiate the packet transfer. Moreover, if the PBCCH is not available, it will listen to the BCCH to get informed about the radio network.



Coding scheme	Pre-cod. USF	Infobits without USF	Parity bits BC	Tail bits	Output conv encoder	Punc-tured bits	Code rate	Data rate (kbits/s)
CS-1	3	181	40	4	456	0	1/2	9.05
CS-2	6	268	16	4	588	132	~2/3	13.4
CS-3	6	312	16	4	676	220	~3/4	15.6
CS-4	12	428	16	-	456	-	1	21.4

Table 2.3. Channel coding schemes in GPRS

2.7.2. Channel coding

Channel coding is used to protect the transmitted data packets against errors. The channel coding technique in GPRS is quite similar to the one employed in conventional GSM. Four different coding schemes are defined to be able to adaptively react to current channel quality (link adaptation) depending on the carrier to interference (C/I) ratio (table 2.3). 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 resulting coding parameters and maximum bit rates are shown in table 2.3. 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.

2.7.3. Data flow

The network-layer protocol data units (N-PDUs or packets) received from the network layer are transmitted across the air interface between the MS and the SGSN using the LLC protocol. First, these N-PDUs are transformed into LLC frames of 1500 bytes. An LLC frame is then segmented into RLC data blocks (29 on the downlink and 31 on the uplink), which are handed over to the MAC layer. Each block comprises four normal bursts in consecutive TDMA frames. A selective ARQ protocol between the MS and BSS provides retransmission of blocks in error by use of a temporary frame identity (TFI). The TFI is included in every block belonging to a particular frame, including retransmitted blocks determined by the ARQ protocol. Furthermore, blocks belonging to frames to/from different MSs can be multiplexed on the downlink/uplink based on the TFI. When a complete frame is successfully transferred across the RLC layer, it is forwarded to the LLC layer.

2.8. Impact of GPRS implementation on GSM network

The primary interest of a GSM operator is that introduction of GPRS should be supported without notable changes in the GSM network. Since GSM has been designed for circuit switched transmission only, introduction of a packet switching technique as GPRS obviously evokes some significant functional and operational changes in the network. The main impacts caused by GPRS on the GSM network are summarized here:

- New network nodes SGSN/GGSN

As seen in section 2.3, two new network nodes are necessary to support packet data routing and transfer: SGSN and GGSN. This causes more traffic on the existing SS7 network, so it increases the SS7 network load. The number of SGSNs/GGSNs depends on the implementation (e.g. the area covered by each SGSN).

- Network and Switching Subsystem (NSS)

A new register called GPRS register (GR), which is implemented as part of the HLR, is necessary in order to store GPRS subscription information. New mobile application part (MAP) functions that support signaling exchange with the GSNs are also added. These new functions result in an increase of the HLR load and in more HLR memory consumption. Due to the fact that every SGSN needs its own authentication and ciphering parameters, also the AuC load increases. Three new interfaces are added: Gr between the MSC/HLR and SGSN, Gc between the MSC/HLR and GGSN and Gs between the MSC/VLR and SGSN. The last one is necessary for allowing combined GPRS/GSM mobility management as well as paging of circuit switched calls within the GPRS network. SMS can be sent not only via GSM but also via GPRS. For this, the SMS nodes are upgraded to support SMS transmission via the SGSN and a new interface called Gd between SMS-MSC and SGSN is necessary.

- Base Station Subsystem (BSS)

Two new units with specific functionality for packet data services are necessary for the GPRS service: the protocol control unit (PCU) and the channel control unit (CCU). The PCU is responsible for LLC segmentation, channel access handling, channel allocation, ARQ and retransmission handling and radio channel management. The CCU is responsible for channel coding, FEC, interleaving and radio measurement. The GPRS standard does not specify exactly how the responsabilities are divided between BSC and BTS, so it is implementation-specific. For instance, PCU can be either in BTS/BSC or even outside BSS, whereas CCU is in BTS. A new interface called Gb interface connects the BSC and the SGSN and a new layer called BSSGP is necessary. The radio interface between BTS and MS (Abis interface) is also upgraded to support GPRS, and new logical link layer and physical layer protocols are defined (see section 2.6).

- Impact on network planning

The GPRS implementation requires some resources to be allocated for GPRS, so changes in radio resource allocation algorithms are necessary (see chapter 3). Furthermore, the introduction of GPRS without allocating new spectrum reduces the capacity and quality of existing GSM services, so new planning strategies are compulsory (see chapter 5).

Chapter 3

Radio resource management in GPRS/GSM networks

This chapter relates the principles of radio resource management for GPRS and describes different radio resource allocation techniques in overlaid GPRS/GSM networks.

3.1. Principles of radio resource management when integrating voice and data services

The integrated services analysis has been a research subject for more than two decades; two types of services, voice and data, compete for same resources in an overlaid wireless network. Both services have different QoS requirements, so the scheme of sharing the radio resources plays an important role in network dimensioning.

Different information transfer modes have been used in cellular networks so far and can be classified as follow :

- *Circuit Switching*: in this mode a traffic channel is dedicated to a user (voice or data) for the entire communication duration. This mode is suitable for real-time applications demanding a continuous flow of traffic, such as speech or video. (e.g. GSM, AMPS)
- *Packet Switching*: in this mode the bandwidth is allocated only in active period (talk spurts or when data users have packets to send). It is suitable for applications which have a bursty traffic behaviour, such as Internet browsing. (e.g. GPRS, CDPD).
- *Hybrid Switching*: this mode supports both circuit and packet switching. (e.g. GPRS/GSM network, CDPD/AMPS network).

The Hybrid Switching, which is considered in this Thesis, can be implemented in three channel allocation methods:

1. *Complete Partitioning* (CP): in this method the available bandwidth is divided in two different parts. Voice users only use one part and data users use the second part.

2. *Complete Sharing* (CS): in this method all the bandwidth is dynamically shared between both kind of users.
3. *Partial Sharing* (PS): in this method data users have their exclusive bandwidth and also can use the unused bandwidth of voice users.

From a GoS perspective, the CS and PS methods are problematic for voice services if no prioritization of voice services over data services takes place.

In general, these different channel allocation policies are a tradeoff between delay, throughput and spectrum utilization, so it is clear that the selection of the optimal one for such a network must be made on realistic estimates of traffic to ensure good performance of both services.

3.2. Allocation of resources for the GPRS service

When a GSM operator decides to offer GPRS-based services within an existing GSM network, it has two alternatives:

- Allocating new spectrum for GPRS services.
- Sharing the current spectrum between GSM and GPRS services.

The first one is the primary way to increase capacity, but the needed investments for new cell sites or new transceivers (TRXs) imply a high implementation cost for the GSM operator. Moreover, the additional TRXs require frequencies and assuming that no new bandwidth is given to the operator’s use, the frequency space should be re-planned. Since even at peak GSM traffic load, average utilization of traffic channels is kept modest in order to keep call blocking probabilities on a tolerable level (see figure 6.3), allocating new spectrum also implies a waste of these radio resources temporarily unused by GSM which could be used for GPRS. For these reasons, it is assumed that the existing radio resources are shared between GPRS and GSM services and no new resources are allocated. In this Thesis, all the GPRS implementations considered do not allocate new spectrum for GPRS services and, therefore, the GSM traffic plays a significant role in GPRS dimensioning and planning.

Since the GPRS is to be integrated into the GSM infrastructure without allocating new spectrum, both services must share the same radio resources. A cell supporting GPRS may allocate resources on one or several physical channels in order to support the GPRS traffic. Such a physical channel is denoted as packet data channel (PDCH). Those PDCHs, shared by the GPRS terminals, are taken from the common pool of physical channels available in the cell. The mapping of physical channels to either GSM circuit switched or GPRS packet switched services can be performed dynamically according to the "capacity on demand" principle described in chapter 3.2.5, depending on the current traffic load and the priority of the service.

3.2.1. Master/slave channel concept and multiframe structure

In order to simplify the logical channel concept, the allocated PDCHs are logically grouped into master channels (MPDCHs) and slave channels (SPDCHs). At least one MPDCH accomodates the PCCCHs and the PBCCH, which carry all necessary control signaling for initiating packet transfer, as well as user data and dedicated signaling. The other SPDCHs only carry PDTCHs, that is, user data and dedicated signaling.

The mapping of PDCHs onto physical channels is based on the definition of complex multiframe structures on top of the TDMA frames. A multiframe structure for PDCHs consisting of 52 TDMA frames is defined. This 52-multiframe consists of 12 RLC blocks of 4 consecutive TDMA frames, two TDMA frames reserved for transmission of the PTCCH and two idle frames. The mapping of the logical channels onto the blocks of the multiframe can vary from block to block and is controlled by parameters that are broadcast on the PBCCH. Besides the 52-multiframe, which can be used by all logical GPRS channels, a 51-multiframe structure is defined. It is used for PDCHs carrying only the logical channels PCCCH and PBCCH and no other logical channels.

3.2.2. Multi-slot operation

GPRS allows a single MS to transmit on multiple timeslots of the same TDMA frame. This results in a very flexible channel allocation: one to eight timeslots per TDMA frame can be allocated for one MS. By this multi-slot operation, the bandwidth assigned to one MS can be varied dynamically and the transfer delay can be reduced, and data rates of nearly 170kbit/s can be theoretically achieved.

A typical GPRS device should be able to perform single-slot and multi-slot operation, but not all eight timeslots have to be used. In fact, the most economical phones use configurations 1:2 (1 timeslot for the uplink and 2 for the downlink) and 1:4 (1 timeslot for the uplink and 4 for the downlink), and are limited to 56kbit/s [14]. On the arrival of a multi-slot call from one

MS, if the available resources are enough to provide its required service, the MS is allowed to transmit its required rate. But if the available resources are not enough to provide its required service, there are different possibilities:

- The network simply rejects the request.
- The network negotiates with the MS to reduce its transmitted rate to the value which the network can provide. The MS accepts the value and send packets at the reduced rate.
- The MS agrees to transmit with the rate which the network can provide, and the network further inquires the MS if it wants to restore its required transmission rate when the network can provide it.
- The MS does not agree to reduce its transmission rate, and the network puts it into the queue until it can provide the required transmission rate.

The use of these different multi-slot schemes is a tradeoff between the data rate achieved and the time spent in the queue (queueing time). In [15] it is shown that the last multi-slot scheme always gives the highest queueing time.

3.2.3. Multiple access and statistical multiplexing gain

In conventional GSM, a channel is permanently allocated for a particular user during the entire call period (whether data is transmitted or not). In contrast to this, in GPRS the channels are only allocated when data packets are sent or received, and they are released after the transmission. With this principle, multiple users can share one physical channel (*statistical multiplexing*), resulting in a much better utilization of the radio resources and increasing the capacity of the system. The ETSI standard GSM 05.02 [16] defines two different medium access modes that should be supported in all MSs: the fixed allocation and the dynamic allocation mode.

In the *fixed allocation mode*, the resources allocated to a particular MS are sufficient to transfer the data it has ready for transmission and are fixed during a certain period of time called the allocation period. Then, different GPRS MSs can be multiplexed on time on the same PDCH depending on the duration of the allocation period. In the *dynamic allocation mode*, an uplink state flag (USF) is used in the downlink direction to reserve the uplink PDCHs for different MSs. The “packet uplink assignment” message includes the list of PDCH/s allocated to the MS and the corresponding USF values per PDCH. The MS monitors the USF/s on the allocated PDCH/s and transmits radio blocks on those which currently bear the USF value reserved for the usage of the MS. This mode provides a more flexible use of the radio resources in general.

The performance of both medium access modes has been analyzed in [17] under single-slot and multi-slot operation cases. For single-slot operation, the dynamic allocation mode performs better than the fixed allocation mode. This better performance is based on the better utilization of resources on every PDCH, which results in a less wastage of radio resources. For multi-slot operation, the dynamic allocation mode performs better when the arrival rate of “packet channel requests” is high, but the fixed allocation mode performs better for low arrival rate of the “packet channel requests”.

3.2.4. Asymmetric usage of uplink and downlink radio resources

In case of circuit switched transmission, the channels are reserved symmetrically in pairs. However, in packet switched transmission, uplink and downlink channels are basically used as independent channel resources [18]; that is, in a certain TDMA timeslot an uplink PDCH may carry data from one MS, while data to another MS is transmitted on the downlink PDCH. The justification is the asymmetric nature of data traffic. For instance, a wireless surveillance video system transmits plenty of data in the uplink direction but only a small part in the opposite direction. However, in data downloading and web browsing the direction is opposite. Since the Internet applications, especially the web browsing, will be the main traffic source for GPRS, this will result in a larger transfer of data from the network to the MSs rather than the other way around.

3.2.5. Dynamic channel allocation (DCA)- capacity on demand concept

According to the requirement for flexible adaptation to different traffic conditions, the number of allocated PDCHs in a cell can be increased or decreased based on GPRS demand. In order to implement this principle, a *load supervision function* must be used in the system and may be implemented as a part of the MAC functionality. This load supervision function may monitor the load of the PDCHs, and the number of allocated PDCHs in a cell can be increased or decreased according to the actual load.

Because the call setup procedure in GSM circuit switched services is rather slow (it takes about 3 to 5 seconds) [18], there is enough time to release one PDCH to be used for a circuit switched call . Therefore, upon resource demand for circuit switched services, some PDCHs must be released as soon as possible. The release can have two alternatives:

- *Immediate Release*: the GPRS user is forced to stop its transmission until resource is available for GPRS again and the channel released by GPRS is allocated to the new circuit switched call.
- *Delayed Release*: the GPRS user can continue its transmission up to some frames or until the ending of packet transmission, before the channel is allocated to the new circuit switched call.

Once the circuit switched call is completed, the channel is again free for GPRS service. This means that circuit switched services have higher priority than GPRS services, unless some channels permanently allocated to GPRS.

The GPRS service does not require compulsory permanently allocated PDCHs. The operator can, as well, decide to dedicate permanently or temporarily some physical channels for GPRS traffic. Otherwise, it may be difficult to have an effective GPRS service in a cell if no channel is dedicated to GPRS when high GSM traffic load, as GSM services have higher priority than GPRS services [18][19]. This should be an adjustable parameter in the BSS; the operator could adjust the parameter based on the utilization of the PDCHs (load supervision function) and the frequency of initiated circuit switched calls.

In the ETSI standard GSM 03.64 [5] the “capacity on demand” principle is described. Details that are related to certain channel allocation strategies are left open and are implementation-specific, so the choice of the GPRS/GSM radio resource allocation algorithm is critical to the performance of both systems. The different radio resource allocation strategies that can be used by the GSM operators are described in section 3.3 and are based in the general principles about radio resource management in overlaid networks seen in section 3.1.

3.3. Radio resource allocation techniques in GPRS/GSM networks

There are two ways for overlaying GPRS onto the GSM network without allocating new spectrum for GPRS:

- Dedicating GSM traffic channels to GPRS only.
- Dynamic sharing of radio resources between GPRS and GSM.

The first way reduces the GoS of GSM services, as it exclusively dedicates N_{gprs} channels to GPRS service. Since these N_{gprs} channels are taken from the common pool of available channels in the cell, this reservation reduces the number of channels available for GSM services, which results in an increase in blocking probability and, hence, reduces the capacity of GSM services. In contrast to the first way, the dynamic sharing of the available channels between GPRS and GSM services presents no impact on the GoS of GSM services if the allocation of traffic channels to GPRS is limited to idle traffic channels and the stolen channels are preempted when requested by the GSM service. This means that GSM services have priority over GPRS services, so the capacity of GSM services is not degraded. Although it creates an additional capacity for GPRS services without degrading GoS of GSM, the GSM service performance will be degraded because outage probability increases and cell service area decreases, due to the additional interference contributed by GPRS packet transmission [7].

The performance of both services can be dramatically affected if appropriate radio resource allocation schemes are not used. In existing literature related to radio resource management in overlaid GPRS/GSM networks [20][21][22][23], three different radio resource allocation techniques can be found, based on the above two ways of overlaying GPRS on the GSM network. Figure 3.1 contains block diagrams of the three techniques.

3.3.1. Complete Partitioning (CP)

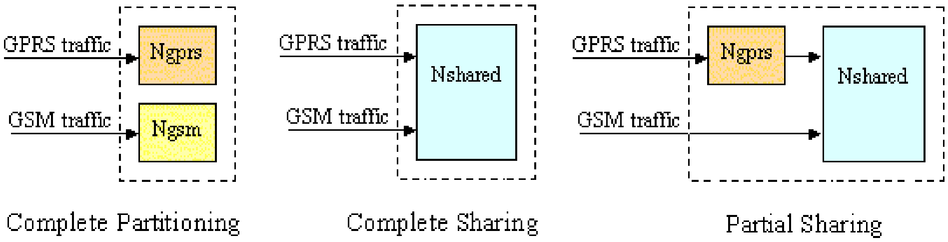
In this technique, full partitioning of radio resources between GPRS and GSM services is performed. The idea is that some channels are permanently assigned to GPRS services only (N_{gprs}) and the other ones are exclusively used by circuit switched services (N_{gsm}). This technique reduces the GoS of GSM if no allocation of new spectrum for GPRS is carried out, as it exclusively dedicates N_{gprs} channels to GPRS service.

3.3.2. Complete Sharing (CS)

In this technique, full sharing of radio resources between GPRS and GSM services is performed. The idea is that all the available channels are shared between both services (N_{shared}), whereby circuit switched services are assumed to have strict priority over GPRS services. Therefore, traffic channels temporarily not used by circuit switched services may be used by GPRS services, but upon resource demand for circuit switched services, de-allocation of these channels must take place. This technique presents no impact on GoS of GSM.

3.3.3. Partial Sharing (PS)

This technique combines the CP and CS techniques in order to enable the GPRS to satisfy different service requirements. The idea is that some channels are reserved for GPRS service only (N_{gprs}), as in CP, and the other ones are shared between both services (N_{shared}), as in CS. This technique impacts both the GoS and the QoS of GSM.



Complete Partitioning Complete Sharing Partial Sharing

Figure 3.1. Radio resource allocation techniques in GPRS/GSM networks

Chapter 4

Performance study of the GPRS service

A detailed performance study of the GPRS service is presented in this chapter based on several studies found in literature.

4.1. Introduction

GPRS performance studies are usually presented for both single-slot and multi-slot operation and can be focused on either the uplink or the downlink.

- In the **uplink procedure**, a GPRS connection consists of three phases: access phase, resource reservation phase and data transfer phase. The *access phase* is contention based and is derived from slotted Aloha technique and flow control procedures. Access messages are sent on the PRACH channel following previous contention algorithm. The main performance parameters of this phase are blocking rate and access delay. In the *resource reservation phase* (call admission phase), the calls that have successfully passed the access phase are queued and are assigned (if possible) the suitable radio resource in order to a priory meet the data transfer requirements (QoS requirements). The main performance parameter of this phase is the queueing time. If sharing the radio resources with GSM (e.g. in CS and PS), another performance parameter is the interruption time, which is included in the queueing time, and the interrupted GPRS calls have higher priority to be allocated resource than the queued calls. Then, the connection enters in the *transfer phase*, where various scheduling strategies can be applied in order to actually ensure the requested QoS for each connection. The main performance parameters of this phase are transfer delay and throughput.
- In the **downlink procedure**, there is only the *transfer phase*, and the main performance parameters are transfer delay and throughput. All the performance studies focused on the downlink procedure make the assumption that there is always sufficient uplink capacity to service the signaling needed for the downlink connections, i.e. for acknowledgement messages.

A further justification for uplink and downlink separated studies is that uplink and downlink are allocated separately in GPRS because of the asymmetric nature of data traffic.

4.2. GPRS performance measures

The performance studies of GPRS are usually focused on three well-known performance measures:

- The *throughput* is the amount of data per second that has been successfully transmitted over the air interface (kbit/s). The throughput specifies the maximum/peak bit rate and the mean bit rate and it measures the efficiency of data transmission in the cell. The throughput only accounts for the time the resources are allocated to an MS, i.e., when the MS is in the transfer phase.
- The *transfer delay* is the time in seconds from the arrival of a message at the source until the whole message is correctly received at the destination, i.e., the data message transmission time.
- The *blocking rate* is the fraction of random access attempts that fail because either the number of contentions or the random access time exceeds a limit.

Further evaluation criteria are access delay, queueing time, interruption time, channel utilization, dropping rate, etc:

- The *access delay* is defined as the time elapsed since a message is generated until the first data burst is sent across the radio interface.
- The *queueing time* is the time spent waiting in the queue since a GPRS call has successfully passed the access phase until the whole message has been sent across the radio interface.
- The *interruption time* is the time that a GPRS connection is stopped because a voice service with higher priority needs its radio resource. It is defined only when sharing the radio resources with GSM (CS and PS techniques), and is included in the queueing time.

These performance measures are usually examined as a function of the input load (kbit/s), which indicates the normalized amount of data related to the channel capacity. The delay parameter defined for QoS (see table 2.2) would include the access delay and the transfer delay as defined here, as well as the transit delay in the GPRS backbone network.

4.3. Highlights of the GPRS performance studies

The analysis of the GPRS performance is a very complicated problem due to the high dimensionality of the problem, especially as multiple classes of MSs and multiple classes of

QoSs are supported in GPRS. However, using simulations and approximation methods is possible to carry out the study of the GPRS performance. The general conclusions that can be drawn from different GPRS performance studies found in literature are:

- GPRS provides efficient utilization of the radio resources, but this efficiency depends strongly on the nature of the data traffic type (see section 4.4).
- The performance of the GPRS service can be enhanced if a few traffic channels are permanently reserved to GPRS (see chapter 4.5).
- The throughput of the GPRS system always behaves like in figure 4.1. When the system is stable, the throughput has an ascending linear tendency and equals the input load if no dropping occurs. But there is a point where the system overloads and the throughout saturates at a maximum value. That is the point where too much users are trying to access the system and collisions take place, or when PCCCHs have become too much slow to give access efficiently to all users without excessive delay, and consequently some access attempts are not successful. At this point, the access delay (see figure 4.1) and the queueing time have an ascending tendency that starts to increase with a higher slope as input load grows, until the system becomes unstable. Therefore, a lower threshold for the maximum number of GPRS users accepted into the system should be taken into account when users want to access the system [19][23]. Then, when the number of users is about to overcome this threshold, the operator should stop giving access to more users (thus fixing a maximum access delay accepted) or, in case it has more resources available, it would assign more PDCHs allowing to increase the number of users. Obviously, the expected number of GPRS users should be less than the maximum number accepted in order to avoid the rejection of new GPRS sessions.

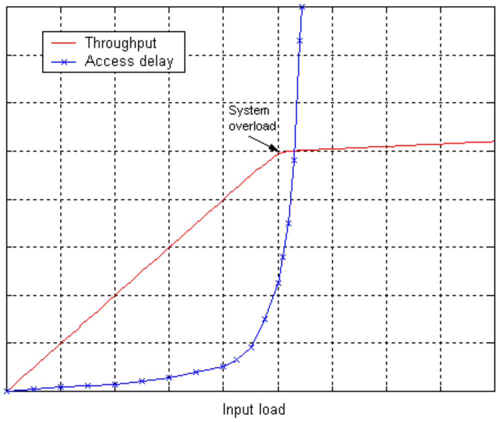


Figure 4.1. Throughput and access delay behaviour in GPRS

- The data rates that can be achieved in the GPRS transfer phase depend on the coding scheme used, so the coding scheme for a GPRS connection could be dynamically adapted to the radio channel conditions (link adaptation) in order to achieve the highest throughput in each moment. The looser coding scheme pattern is used, the faster data rates that can be offered (see table 2.3). Furthermore, GPRS supports frequency hopping, which improves the throughput [24].
- There is no significant difference in the throughput per slot achieved between single-slot and multi-slot operation [9]. Only in the MPDCH, the maximum throughput achieved is lower because this channel has to handle both traffic and control information. The SPDCHs only have to carry traffic, so the throughput per slot achieved is the same for both kinds of connections [10].
- Transfer delay is smaller in the case of multi-slot assignment, since the time between slots belonging to one transmission is shorter due to the parallel assignment [9][10] .
- Blocking rate/access delay and queueing time are higher for multi-slot operation [15], but they could be reduced by using an efficient radio resource allocation strategy (see section 4.4) and a flexible multi-slot service scheme (see section 3.2.2).

The daily distribution of GPRS traffic is hard to predict, so in lack of realistic GPRS traffic profiles, in all the studies it is usually assumed that the GPRS load peaks will occur at the same time that GSM load peaks, which creates a worst case situation. As a result, the actual data rate will be highly dependable on these transient traffic profiles besides the radio resource allocation strategy. Then, assuming that the daily packet data traffic profile is not identical to the circuit switched one, the load peaks will not overlap creating even more capacity than the obtained in the performance studies.

4.4. Influence of data traffic patterns in GPRS performance

All the studies about the GPRS performance show that the efficiency of GPRS depends strongly on the nature of the data traffic model [9][10][23][25][26]. Since a unique protocol is provided by GPRS for all the types of data traffic, GPRS performance is highly sensitive to the data traffic characteristics, especially in high input load conditions [25]. Consequently, optimization of GPRS should also take into account as much as possible the real characteristics of the data traffic.

Data traffic can have different characteristics from highly bursty data transmission of short packets (few tens of bytes per message) to infrequent transmission of larger volumes of data (few kbytes per message). Depending on the data traffic type, distinct parameter setting should be considered for achieving optimal performance. According to the ETSI-SMG GPRS ad hoc evaluation guidelines [27], three traffic models should be implemented in order to evaluate the performance of GPRS for each traffic type:

- Mobitex model

This model is based on statistics collected from a fleet management application using the Mobitex wireless packet data network in Sweden. It is used to simulate *very frequent transmission of short packets*, where the packet size is uniformly distributed between 15 and 45 bytes for the uplink and between 58 and 172 bytes for the downlink.

- Railway model

This model is based on an assessment of railway application requirements. It is used to simulate *medium frequent transmission of medium sized packets,* where the packet size is modeled by a negative exponential distribution with average equal to 170bytes and truncated at 1000bytes (maximum message size).

- Funet model

This model is based on statistics collected on e-mail usage from the Finnish University and Research Network. It is used to simulate *infrequent transmission of large packets*, where the packet size is modeled by a Cauchy distribution truncated at 10kbytes (maximum message size) and with an average around 1770bytes.

In [9] and [25], a performance study of the **GPRS uplink procedure** with single-slot operation is carried out using the above data traffic models and under medium/high input load conditions. Both studies consider GPRS traffic only and use a fixed number of traffic channels for data transmission, without taking into account the value of N_{gsm} (the GSM service). [9] uses N_{gprs}= 8 and [25] uses N_{gprs}= 2, but the conclusions that can be drawn from the results obtained are the same for both studies:

- It is shown that throughput is higher when data traffic consists of large packets rather than short ones, that is, for the Funet model type. The reason for the smaller throughput in the case of the Mobitex model type is the generated packet sizes. The Mobitex model generates small packets that fit in one or two RLC 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. Then, the throughput achieved is very low.

Furthermore, more signaling information in the form of acknowledgements and channel reservation needs to be transmitted relative to the generated amount of data, so the throughput decreases.

- It is also shown that for highly bursty data traffic like Mobitex model type, the bottleneck is at the access phase, and the PRACH channel saturates at medium/high load. The reason for this PRACH saturation is also the generated packet size. The Mobitex model generates small packets that fit in one or two RLC blocks. Since each generated packet needs a random access attempt, then each one or two RLC block implies a random access attempt, so more collisions occur and the signaling channels are overloaded. Therefore, the blocking rate and access delay in case of the Mobitex model type are higher and increase more as input load goes up.
- For the Railway model the access phase can become also a bottleneck, but only with very high input loads. This is also due to the generated packet sizes; although the Railway model generates packets up to 1000bytes long, an analysis of the probability density function (PDF) shows that most of the packets are smaller than six RLC blocks, so the same argumentation as for the Mobitex model can be applied.
- The queueing time (interruption time) is higher for the Funet model type, so the resource reservation phase can become a bottleneck for this traffic type if N_{gprs} is very low (just 1 or 2 channels as in [21][22]).

To evaluate the performance of the **GPRS downlink procedure** with single-slot operation, a study for various input loads has been made in [26] using the above data traffic models. The study considers GPRS traffic only, without taking into account the value of N_{gsm} (GSM service), and it uses $N_{gprs}= 7$. The study shows that generally the performance is more optimum for the Funet model type, so GPRS is better suited to the transmission of larger packet sizes in the downlink. This is shown by the higher mean throughput and lower normalized mean delay (access delay + transfer delay) for the Funet traffic over Railway and Mobitex traffic. The authors suggest that this is a result of the transmission overheads becoming more significant as the packet size reduces. With shorter packets there is more overhead per unit time, and consequently lower throughput.

4.5. GPRS performance using different radio resource allocation techniques

Performance of packet data services is strongly influenced by efficient use of the scarce radio resources, so the technique used to allocate the radio resources will strongly impact on the performance of GPRS.

4.5.1. GPRS performance with the CP technique

This technique allows for more control of the relative blocking/dropping probabilities for circuit switched services, as different levels of priority for GPRS and GSM can be achieved by changing N_{gprs} and N_{gsm} [21]. Moreover, dedicating a fixed number of channels exclusively to GPRS allows a substantial improvement of the delay performance for GPRS connections, although this improvement becomes less significant as N_{gprs} increases [19]. The blocking rate for GPRS services is independent of the voice traffic load, as different random access channels are used for contention by both services. These N_{gprs} channels also ensure some throughput at all times, even at high voice load.

The main weakness of this technique is that the above improvements are achieved at the expense of overall usage of the network [21], because we may have the undesirable situation in which some traffic channels from the N_{gsm} remain idle while data packets are required to decrease their throughput or are delayed because they can not use the unused traffic channels in N_{gsm}. It is well known that even at peak GSM traffic load the average utilization of traffic channels is not very high because of statistical traffic fluctuations (see figure 6.3), so due to bursty nature of GPRS applications it is a wastage of radio resources if the data traffic is not allowed to use any of these idle traffic channels. This inefficient channel utilization increases at low voice load, because more unused traffic channels exist and are wasted. To alleviate this inefficiency in channel utilization, the PS technique is proposed.

4.5.2. GPRS performance with the CS technique

In general, this technique results in maximum usage of the available bandwidth (maximum channel utilization) and is very attractive, since it provides a very low cost packet data service without penalizing the performance of the circuit switched services, with no radio resources exclusively dedicated to GPRS [21]. However, the resulting delay performance for packet data services may be critical when the voice traffic load is high, as circuit switched services have strict priority over GPRS services, and the interruption time becomes a very important performance measure [19]. The performance characteristics of this technique in terms of delay are appropiate for data services that have no strict requirements on the QoS and can tolerate a few seconds for the average access delay and tens of seconds for the peak access delay [19]. However, this technique is not suitable for data services that have strict requirements for delay, and in order to satisfy these delay constraints it is necessary to exclusively reserve N_{gprs} channels (as in PS or CP technique).

Not only the delay performance of data services is affected when the voice traffic load is high, but also the blocking rate increases because the heavy circuit switched traffic may consume almost all N_{shared} channels. Moreover, as both services use the same random access channel (RACH), the blocking rate is even higher because no dedicated PRACH is used for GPRS. It is also not possible to guarantee some QoS in terms of throughput for the GPRS service.

With the CS technique the single-slot users can achieve access to the system with higher probability than multi-slot users. This tendency becomes more pronounced as the overall traffic load increases and under heavy loads tends to completely exclude the multi-slot users. Therefore, it can be concluded that the CS technique performs better when data services have no strict requirements on the QoS and the voice traffic load is not very high, and that with this technique the multi-slot operation should not be allowed unless very low voice load.

4.5.3. GPRS performance with the PS technique

This technique always gives the best GPRS performance. At low voice load, the GPRS performance is very close to the ideal case, offering significantly higher throughput than the CP technique, where all the unused traffic channels by the GSM service are wasted. At high voice load, the GPRS performance degrades less rapidly than the CS technique, and guarantees a minimum throughput equal approximately to the CP technique due to the N_{gprs} channels [22]. The multi-slot operation can be implemented because N_{gprs} channels are dedicated to GPRS services and brings important benefits in terms of reducing delays and improving efficiency.

In general, this technique is best able to adapt to the network load profile and it allows more flexibility in catering to the QoS requirements of the different user types while maintaining high network usage [21]. For these reasons, the GSM operator should consider to employ it in order to allow the system to function flexibly under a wide range of offered traffic loads. Furthermore, since data traffic tends to cause drastic peaks between low traffic periods, if the system is able to quickly respond to the peaks (by changing N_{gprs} and N_{shared}), both types of traffic will be served well [24].

Chapter 5

Impact of GPRS implementation on existing GSM services

This chapter discusses the impacts caused by the GPRS implementation in a GSM network on the existing GSM services, especially focusing in their reduction of capacity. Several ways of counteracting this reduction of capacity are proposed, and special attention is paid to the so-called handover prioritization schemes.

5.1. Interference effects- impact on quality of existing GSM services

As seen in section 3.2, allocating new spectrum for GPRS services implies a high implementation cost for the GSM operator and a waste of the radio resources temporarily unused by GSM. Therefore, it is assumed that GPRS will use the same frequencies as GSM and no new resources for GPRS will be allocated. Obviously, the introduction of GPRS into GSM networks without allocating new spectrum will increase the interference probability of existing GSM services. In addition, every PDCH (physical channel allocated to GPRS) is shared by a few data users simultaneously (multiple access). Then the cochannel interference to the GSM users might vary rapidly and dramatically in the time interval from 20ms to a few seconds depending on the transmitted packet data size, because the locations of GPRS users could be largely different [28]. This effect could drive the overlaid GPRS/GSM system into an unpredictable and unstable situation besides causing a degradation of the quality of existing GSM services, so a preliminary resource planning for GPRS is required to guarantee the QoS for GSM users.

A method to calculate the outage probability of the GPRS/GSM network for both the non-frequency hopping and the frequency hopping systems has been developed in [7][28]. Their results show that GPRS affects on the QoS of GSM users of the network with small reuse factor are higher than that of the network with large reuse factor. Furthermore, the outage probability near to the cell border area will increase and the real served area of a cell may be reduced, which implies that GPRS may cause a higher handover dropping rate to GSM services [29]. Since GPRS increases the outage probability of existing GSM services, all those unused channels might not be used for carrying GPRS traffic; then a maximum number of GSM channels to be allocated for GPRS (either temporarily or permanently) should be established in order to guarantee the QoS of existing GSM users. This maximum number of unused GSM channels allocated to GPRS would depend on the difference between the outage level of the existing GSM network and the maximum acceptable outage level.

In this Thesis, the effects of GPRS on quality of existing GSM services are not evaluated because they have been studied in previous works [7][28]. The goal here is to study how GPRS impacts on capacity of existing GSM services, which is discussed in the next point.

5.2. Blocking effects- impact on capacity of existing GSM services

Ideally a GSM operator would like to retain the same capacity for GSM when GPRS is introduced, so introduction of GPRS packet data services should not have any effect or little effect on the existing GSM circuit switched services. As seen in section 3.3, no exclusive reservation of existing radio resources for GPRS service –CS technique– has no impact on the capacity of GSM services because of the GSM priority. However, there are several reasons that make necessary reserving some channels for GPRS (N_{gprs}) in order to guarantee the QoS of GPRS service:

- The HSCSD service [6] supports as well multi-slot services and has higher priority to access the radio resources than the GPRS service. Then, a multi-slot HSCSD connection may cause massive blocking of GPRS users. Therefore, as the introduction of the HSCSD services into the GSM system takes place, it might be difficult to guarantee the QoS of GPRS if no channel is dedicated to GPRS.
- As the GPRS subscribers number grows, the GPRS traffic load increases and some minimum number of traffic channels should always be reserved for GPRS to guarantee some minimum service level.
- As multiple classes of QoS and multiple classes of terminals with different multi-slot capabilities and multiple applications are introduced, if no channel is dedicated to GPRS it might be difficult to ensure the GPRS performance for these terminals.
- As seen in section 4.4, the resource allocation technique which provides enhanced GPRS performance is the PS technique, so some dedicated channels are necessary to have an effective GPRS service.

It is obvious that if exclusive reservation of channels for GPRS is carried out by the GSM operator in order to guarantee some QoS of GPRS service, such reservation will reduce the number of channels available for existing GSM services. This reduction in the GSM channels will obviously increase the blocking probability of circuit switched services and, hence, reduce the capacity of these services.

5.2.1. Difference between new calls and handovers

The offered traffic by the existing GSM circuit switched services in a cell comprises two kind of calls:

- *New calls*: calls that are initiated in the cell.
- *Handovers*: calls that are handed over from other cells.

Handover requests and new call attempts compete for the same radio resources. At a busy BTS, new call attempts which fail because there are no available channels are called *blocked calls*. Handover requests which must be turned down because there are no available channels are called *handover failures*. When no priority is given to handover requests over new call attempts, no difference exists between these when allocating a channel, and then the probabilities of new call blocking and handover failure are the same. Therefore, the increase in both probabilities due to N_{gprs} is also the same. However, from the user's point of view, forced termination of an ongoing call is clearly less desirable than blocking a new call attempt, whose effect is just to force the user to repeat his access request at a later time. As a result, handovers are usually treated with a higher priority than new calls, and probability of handover failure is a major criterion in performance evaluation of existing GSM services. This handover priority is particularly important when relatively small size cells or microcells are used, because in this case the number of handovers per active call is higher and then the effectiveness of handover procedure has a significant impact on the teletraffic performance of the cellular network.

5.2.2. Methods for counteracting the reduction of capacity of GSM services

There are several ways of counteracting the reduction of capacity of existing GSM services due to GPRS implementation with N_{gprs} dedicated channels. These ones are proposed:

- New frequency assignment strategies

In this Thesis a fixed frequency assignment strategy is considered, that is, a set of radio frequencies are permanently assigned to each cell site (fixed number of channels). By using other frequency assignment strategies (table 5.1) it is possible to increase the capacity in a cell site, because they make more efficient utilization of the available spectrum, but the high degree of complexity of the algorithms employed at the BSC/MSC is an important drawback.

- New bandwidth for the operators

As the number of GPRS users and the number of operators increase, the traffic load increases and clean frequencies become hard to find. Then, it becomes necessary to allocate another frequency band to ensure sufficient capacity. GSM uses the frequency band 900 MHz (GSM900), and extra bands 1800 MHz (GSM1800) and 1900 MHz (GSM1900) [3]. The new bandwidth ensures more capacity for the operator’s use and can be used for both increasing the capacity of existing GSM services and increasing the capacity of new GPRS services. The problem is the same old story, the scarce available spectrum. Furthermore, the needed investments for new cell sites or new TRXs imply a high implementation cost for the operator.

Fixed assignment	*Basic fixed*
	Simple borrowing
	Hybrid
	Borrowing with ordering
Flexible assignment	Scheduled
	Predictive
Dynamic assignment	Call-by-call optimized

Table 5.1. Frequency assignment strategies

- New TRXs without allocating new bandwidth

Another possibility of increasing the capacity is installing new TRXs in the existing cell sites using the current spectrum. The main problem is the implementation cost for the operator. Moreover, these additional TRXs require frequencies and assuming that no new bandwidth is given to the operator’s use, the frequency space should be re-planned.

- Directing GSM traffic in a multilayer network

Due to the demands of complete coverage and sufficient capacity, different cell sizes and multiple layers of cells have been built. A multilayer network is often referred as a hierarchical cell structure (HCS). A way of increasing the GSM capacity would be directing circuit switched traffic or packet switched traffic to different layers in order to divide traffic. Due to the fact that GPRS traffic cannot perform network control cell reselections at an early stage [24], circuit switched traffic could be directed to another layer (e.g. from a microcell to an overlaid macrocell) when possible. This can be done just by handover control in the active mode. Thus, capacity of existing GSM services and new GPRS services could be increased.

- For future UMTS networks, handover between GPRS and UMTS

An interesting future scenario is the handover between GPRS and future universal mobile telecommunications standard (UMTS) networks [30]. A handover algorithm which provides seamless handover between GPRS and UMTS is presented in [31]. This algorithm uses the mobile-controlled handover (MCHO) scheme, in contrast to GSM which uses the mobile-assisted handover (MAHO) scheme. The reason is that when handover is required between two different access networks, it is simpler to initiate the handover by the MS rather than going through the respective networks. Due to this handover between GPRS and UMTS, the GPRS load in a BTS can be reduced, so some of the GPRS dedicated channels (N_{gprs}) can be released to be used by GSM, thus increasing the capacity of GSM services.

- Queueing of new call attempts

Queueing of new call attempts is feasible because new calls are considerably less sensitive to delay than handover requests. On the arrival of a new call attempt, if all channels are occupied, the call is queued according to a first-in-first-out (FIFO) discipline. Then, one new call attempt is served only when a channel is available and no calls exist in the queue. Queueing of new call attempts reduces considerably the probability of new call blocking, but it can cause the probability of handover failure to rise to an unacceptable level if no handover prioritization schemes are used simultaneously.

- Handover prioritization schemes

As seen in section 5.2.1, the reduction of capacity of GSM services becomes particularly critical in the case of handover traffic, because of its relative importance over new call attempts. The probability of handover failure can be decreased by giving some form of priority to handover requests over the new call attempts. Then, the different radio resource allocation techniques seen in section 3.3 can be used together with methods for decreasing the probability of handover failure by prioritizing handover requests over new call attempts at the expense of a tolerable increase in call blocking. These methods are known as *handover prioritization schemes* and are explained in detail in the next section.

5.3. Handover prioritization schemes

Handover prioritization schemes are a way of improving the GoS of GSM services by prioritizing handover requests over new call attempts. Handover prioritization schemes can be seen as radio resource allocation strategies that allocate channels to handover requests more readily than to new calls; the objective is to minimize the probability of forced termination of ongoing calls due to handover failures. Various handover prioritization schemes have been studied in the past by many researchers [32][33][34][35][36]. Three generic handover prioritization schemes are:

- Reserving a number of channels exclusively for handovers .
- Queueing handover requests.
- Sub-rating an existing call to accommodate a handover.

Other prioritization schemes can be viewed as variations or combinations of these.

In general, handover prioritization schemes result in a decrease in handover failures and an increase in call blocking which, in turn, reduces the ratio of carried-to-offered traffic. This tradeoff is inevitable, and the best scheme would be that one which provide lower probability of handover failure at the same time that less call blocking and less reduction in the admitted traffic. Moreover, if this high performance can be achieved with low implementation complexity and low cost, all the better. Nevertheless, it was found that there is always a tradeoff between the performance of this generic priority schemes and their implementation complexity [37].

5.3.1. Non-prioritized scheme (NPS)

When no priority is given to handover requests over new call attempts, the BTS handles both types of calls (new calls and handovers) in the same way and, hence, the same fraction of either calls will be unsuccessful. Therefore, the new call blocking probability and the handover failure probability will have the same value, which can be found theoretically using the Erlang-B formula

$$P_{nb} = P_{hf} = \frac{\dfrac{A_{off}{}^{C}}{C!}}{\displaystyle\sum_{k=0}^{C} \dfrac{A_{off}{}^{k}}{k!}} \qquad (1)$$

where C is the number of available traffic channels. This scheme is referred to as the non-prioritized scheme, and is the most typically employed by cellular technologies.

5.3.2. Reserved channel scheme (RCS)

This scheme is the easiest one to implement together with the NPS and consists of reserving a number of channels exclusively for handovers requests (N_{ho}) from the common pool of channels which can be used for GSM services (N_{shared}). Then, the N_{shared} channels are divided into two different groups: the *common channel group* (N_{com}) and the *reserved channel group* (N_{ho}): the N_{com} channels can be used by new calls as well as handovers, whereas the N_{ho} channels can only be used by handovers. There are two types of reservation:

- Pre-reservation (RCS-pre)

On the arrival of a new handover request, this will be allocated in the reserved N_{ho} channels for handovers. If N_{ho} is full, the handover request will then contend with new call attempts for a channel in the common channel group (N_{com}). This ensures that even under heavy loads a certain minimal handover traffic will be admitted.

- Post-reservation (RCS-post)

On the arrival of a new handover request, this will contend with new call attempts for admission into the common channel group (N_{com}). If N_{com} is full, it will be allocated in the reserved channel group (N_{ho}) for handovers. This post-reserved pool ensures that even under heavy relatively loads, extra priority is given to handovers.

N_{ho} can be a fixed or a dynamically adjustable parameter in the BTS/BSC/MSC, and its optimum determination requires knowledge of the traffic patterns. Reserving channels for handovers means less channels are being granted to new calls, so the blocking probability of new calls may significantly increase, and the total carried traffic is reduced (chapter 6 will show it). This disadvantage can be overcome to a certain extent by allowing the queueing of new call attempts. Having exclusive handover channels contributes to decreasing the effectiveness of the system frequency reuse plan [38] and is seen to bear the risk of innefficient spectrum utilization [39], so careful estimation of channel occupancy time distributions is essential for determining the optimum number of N_{ho} channels. An analytical model for this scheme has been studied in [32].

5.3.3. Queueing priority scheme (QPS)

In order to understand the possibility of queueing handovers, it is necessary to review the handover process (see Appendix 1). Queueing of handover requests is made possible by the existence of the time interval the MS spends in the handover area (degradation interval), where it is physically capable of communicating with both the current and target BTS. The fact that a successful handover can take place anywhere during this interval marks a certain amount of tolerance in the delay for the actual channel assignment to the handover request. On the arrival of a new handover request, if all channels are occupied in the target BTS, the handover request is queued and the MS continues to use the old channel with the current BTS until a free channel becomes available in the target BTS. One new call in the target BTS is served only when a channel is available and no handover request exists in the queue. If any channel is released while handover requests are queued, the released channel is assigned to a handover in the queue. The "next" handover to be served is selected based on the queueing policy. If no channel is available after the mobile moves out of the handover area (i.e., the degradation interval expires), then the call is forced to terminate.

The queueing scheme is only applicable to cell border scenarios where no sudden decays of signal level happen frequently, that is, when handovers take place in line-of-sight (LOS) cell borders. Therefore, handover queueing schemes should be avoided in cell border scenarios where the *street-corner* effect is present, because the time for a channel to be assigned in the target BTS could be very short due to this effect.

Queueing of handover requests effectively reduces the probability of handover failures at the cost of slightly increasing the new call blocking probability, but the ratio of carried-to-admitted traffic is roughly the same as in the NPS [34] (chapter 6 will show it). The choice of the queueing discipline also influences the performance of queue-based handover prioritization procedures:

- ❐ FIFO priority queueing (QPS-FIFO)

With the FIFO queueing discipline, if a handover request finds all channels occupied in the target BTS, the request is queued according to a FIFO discipline, i.e., the last handover request joins the end of the queue and the first to be served is the first in the queue (the earliest one to arrive in the queue).

❐ Measurement-based priority queueing (QPS-MBP)

This queueing discipline is a non-preemptive dynamic priority (time-dependent) queueing discipline and it is called measurement-based because the queueing discipline depends on the power measurements on the radio channels. During the time interval the MS spends in the handover area, its communication with the current BTS degrades at a rate depending on various factors, such as its velocity and direction. This degradation rate is easily monitored by means of radio channel measurements, usually taken by the MS and submitted to the network (remember MAHO procedures of the GSM sytem [3]). Then, the handover area can be viewed as regions marked by different ranges of values of the power ratio, corresponding to the priority levels such that the highest priority belongs to the MS whose power level is closest to the receiver threshold. On the other hand, the MS that has just issued a handover request has the least priority. The power levels are monitored continuously, and the priority of an MS dynamically changes depending purely on the power level it receives while waiting in the queue. Obviously, the last comer joins the end of the queue, but the queue is dynamically reordered as new measurement results are submitted. A queued MS gains higher priority as its power ratio decreases from the handover threshold to the receiver threshold. When a channel is released, it is granted to the MS with the highest priority.

The FIFO queueing discipline does not consider the rate of degradation in the radio channel, so ties within priority classes are broken and the probability of handover failure is higher than in the MBP queueing (chapter 6 will show it). The queueing can be performed at the BTS/BSC or the MSC depending on the intelligence distribution between these cellular network components. The QPS adds extra implementation complexity (compared with the NPS and the RCS) to manage the waiting queues, and modifications to the BTS/BSC/MSC and MS hardware/software are required. The performance of the QPS-MBP is roughly the same as the QPS-FIFO, but its implementation is more complex [34]. Some implications of the cost of this scheme are described in [35]. An analytical model for this scheme has been proposed in [33][34].

5.3.4. Sub-rating scheme (SRS)

The SRS scheme creates a new channel for a handover request when all the channels are occupied by sub-rating an existing call. Sub-rating means that an occupied full-rate channel is temporarily divided into two channels at half the original rate: one to serve the existing call and the other to serve the handover request. The generic protocol required to sub-rate a traffic channel is described in [35]. This scheme always gives the best handover performance (minimum probability of handover failure) without degrading the probability of new call blocking, but its implementation complexity is very high [35]. The penalty is the reduction of voice quality –reduction of throughput in case of circuit switched data connections– during the time which the calls –connections– are sub-rated to accommodate the handovers. Another important drawback is that MSs that are equipped with the sub-rating capability may be more expensive. The costs of this scheme are discussed in [35], as well as the impact of continuing the call –connection– on a half-rate channel (which may have lower voice quality or increase battery drain and delay). An analytical model for this scheme has been studied in [35].

5.3.5. Hybrid schemes (HS)

There is the possibility of a combined use of the different handover prioritization schemes seen before. For instance, it is possible to reserve N_{ho} channels exclusively for handovers at the same time that allowing queueing of handover requests; this would have the effect of reducing the number of handover requests to be queued. Another possibility is to use the RCS-pre and the RCS-post schemes at the same time [36]. A random number between 0 and 1 is generated in the BTS/BSC/MSC using some software installed in it; if this number lies between 0 and 0.5, the RCS-pre is performed for handover calls; if not, channel allocation as in the RCS-post is performed.

Chapter 6

Simplified case study of a GPRS/GSM network

To illustrate a more practical approach about the impacts studied in the previous chapter, this chapter evaluates the teletraffic performance of a single cell belonging to a GPRS/GSM network by using an event-driven simulator.

6.1. Simulation methodology

The performance of a cellular network can be investigated by using either simulation or analytical models (or a combination of both). The analytical models give exact and more general results, but usually require restrictive assumptions, especially for complex systems. In contrast, simulation models are preferred when aiming at the detailed study of the behavior of a specific cellular system covering a given area, because no constraints are in the model building (modeling is often straight forward). In this Thesis, due to the inherent complexity of the channel allocation schemes to implement, no analytical models are studied (they have been properly referenced), and all the performance parameters are evaluated using computer simulation.

To illustrate a more practical approach, a simplified case study of a GPRS/GSM network is studied using an *event-driven simulator*. The simulator is focused on the air interface (U_m interface) only, concretely on the channel assignment process. In fact, the air interface mainly determines the teletraffic performance of the cellular network. The event-driven simulator has been implemented using a simulation library developed in C++ programming language. This simulation library is based on a C++ class library called CNCL developed in the Aachen University of Technology, Germany [40]. The simulation library comprises the following modules:

- *Random numbers*: This module provides two types of random number generators (linear congruence and multiple linear congruence generators), which are crucial in simulations . These random number generators are used by the random distribution classes to generate random numbers with the desired distribution.

- *Statistical evaluation*: This module provides several methods for statistical evaluation of simulation results.
- *Container classes*: This module provides generic containers that can contain any object, e.g, single linked lists, doubly linked lists, queues.
- *Event-driven simulation*: This module provides a set of classes for performing event-driven simulations.

The class hierarchy of the simulation library is given in Appendix 2.

6.2. System model

6.2.1. System parameters

The simulation is focused only on one cell of the overlaid GPRS/GSM cellular network, whose behavior is isolated from those of the other cells, which are collectively described only through the handover requests toward the investigated cell. The focus of attention on a single cell has no penalty because offered traffic load is allowed to vary, so that the single cell can realistically reflect the behaviour of a real cellular system. The simulation is focused on the uplink procedure, where resource contention and resource reservation take place. The offered traffic in the cell comprises calls that are initiated in the cell (new calls) and calls that are handed over from other cells (handovers). The traffic models used to simulate both traffic sources are explained in the next section.

The penetration factor of GPRS service is expected to be higher in urban/suburban areas, so the type of cell to study should be common in these areas. Therefore, the cell under study is chosen to be a ***microcell***, that is, a cell with a relatively small size. In microcellular scenarios the number of handovers per active call is higher than in macrocellular ones because a mobile will have to change BTSs at a much higher rate [41], so the chances of a handover failure due to a lack of a free channel are also higher. Then, in microcellular environments the handover procedure plays an important role on the overall teletraffic performance of the system, and it will be even more important to use clever handover prioritization policies to keep handover failure probability at a low level. Common microcell radius are between 200m and 1km [42]. R_{micro} = 800m is assumed for the simulation (residential area). Furthermore, it is considered that the users in cell borders are always in LOS with the microcell's BTS, in order to avoid the street-corner effect [42]. Thus, QPS schemes are also applicable.

For simplicity, a fixed frequency assignment strategy is employed, but the simulation model could easily be extended to work with any frequency assignment strategy (see table 5.1). A typical GSM system normally has 3 or 4 carriers (TRXs) per microcell [29]. Although changes in the frequency reuse factor could change the number of carriers in each cell, it is assumed that the number of carriers/TRXs in the microcell is fixed and equals $N_{trx} = 4$ regardless the frequency reuse factor. Then, $N_t = 32$ physical channels are available in the cell (every carrier is divided into 8 timeslots [3]). It is assumed that $N_{sig} = 3$ channels are reserved for network signalling, thus, only $N_{ch} = 29$ traffic channels are available for carrying user's information.

As seen in chapter 4, the PS technique provides the best performance for the overlaid GPRS/GSM network, so it is considered that when GPRS implementation into the existing GSM network, the PS technique will be implemented. Then, N_{gprs} channels are exclusively dedicated to GPRS and the remaining channels $N_{shared} = N_{ch} - N_{gprs}$ are shared by GSM and GPRS services. As in the N_{shared} channel pool GSM services have priority with pre-emption over GPRS ones, the GPRS traffic is carried in these channels without affecting the capacity of existing GSM services (the quality is affected because of the increase in the interference probability), and capacity for GSM services in these channels can be calculated without taking into account the GPRS traffic.

In every simulation values of N_{trx}, N_{sig}, N_{ch}, N_{gprs} and N_{shared} are assumed to be fixed, i.e., the channels are allocated in a fixed manner (FCA) and no dynamic changing based on traffic load supervision is implemented.

6.2.2. Traffic and mobility models

The arrival of GSM calls to the cell is the superposition of two processes corresponding to newly initiated calls within the cell (*new calls*) and calls handed over from the neighboring cells (*handovers*). It is assumed that new calls and handover requests are both generated according to a Poisson process with an arrival rate λ_n and λ_h repectively. Then the time between new call arrivals and between handover requests are both exponentially distributed with means $1/\lambda_n$ and $1/\lambda_h$ respectively. Calls that are initiated in the cell can be divided into those that complete inside the cell and those that are handed over to other cells. In the same way, handovers can also be divided into calls that terminate in the cell and those that continue to the other cells. Therefore, a channel could be occupied by the arrival of a new call or a handover, and it could be released either by completion of the call or a handover to other cell.

The time spent by a user on a particular channel in a given cell is defined as the *channel holding (or occupancy) time*.

Although the channel holding time is taken equivalent to the *call duration time* in the fixed telephone network, it is often a fraction of the total call duration in a cellular mobile network. Therefore, a knowledge of the channel holding time PDF is necessary to obtain accurate results. In general, the channel holding time is a random variable which is a function of the system parameters such as cell size, user location, user mobility and call duration time [43]. The PDF of the channel holding time is characterized in [43] using *cell residence (or sojourn) time* distributions for new calls and handovers under general mobility conditions . It is found that the distribution function of the channel holding time in a single cell follows a negative exponential distribution (figure 6.1), that is, probability that any randomly selected channel holding time will equal or diminish time duration t is

$$F_{T_{ch}}(t) = P\left(T_{ch} \le t\right) = 1 - \exp^{-\mu_{ch} \cdot t} \qquad (2)$$

where $\overline{T_{ch}} = 1/\mu_{ch}$ is the mean channel holding time of all calls (new calls and handovers), which depends on different parameters such as mobility, cell size and mean call duration time. In general, as the cell size increases, the mean channel holding time approaches the mean call duration time, which can be expected [43].

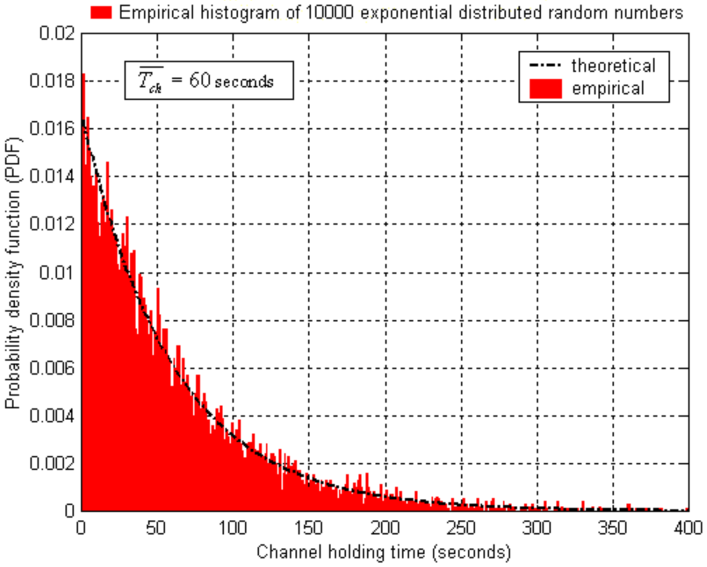


Figure 6.1. PDF of the channel holding time

Handover problems are only expected with moderate/high velocities of the mobiles [34]. Hence, the simulation is carried out considering medium mobility users, that is, moderate speeds of the mobiles. A normal distributed speed with mean $\overline{V} = 30$ km/h and standard deviation equal to 20km/h and truncated at [0,100]km/h is assumed [43] (see figure 6.10). For a cell radius of R_{micro} = 800m, and assuming that mean call duration time is $\overline{T}_{cd} = 120$ seconds and average velocity is $\overline{V} = 30$ km/h, the mean channel holding time is $\overline{T}_{ch} = 60$ seconds [44]. Although the handover traffic is affected by the user mobility, the call duration time distribution and also the new call traffic, in the simulation it is considered as an independent parameter in order to simplify the study. Then, the 35% of the total offered traffic is considered to be caused by handover requests ($f_{ho} = 0.35$).

Changes in the user mobility should have no apparent effect on the results of the simulation (regarding the overall teletraffic performance). When the user mobility increases, users are more likely to move to another cell during the call, and two effects are observed: first, the channel occupancy times become shorter ($\downarrow T_{ch}$), and second, the handovers arrival rate becomes higher ($\uparrow \lambda_h$, $\uparrow f_{ho}$), while the total offered load is about the same. These two conflicting effects balance against each other, so the results would be rather similar.

The total call arrival rate in the cell is the sum of the arrival rates of new calls and handovers

$$\lambda_t(calls/s) = \lambda_n + \lambda_h \tag{3}$$

Then the total offered traffic to the cell will be

$$A_{off}(Erlangs) = \lambda_t / \mu_{ch} = A_n + A_h \tag{4}$$

The total offered traffic (A_{off}) is varied to study the cell under increasing load conditions while the fraction of the total offered load due to handovers is kept fixed to 35% ($f_{ho} = 0.35$), as said before. Then

$$A_h = f_{ho} \times A_{off} \quad , \quad A_n = (1 - f_{ho}) \times A_{off} \tag{5}$$

6.2.3. Models for the handover prioritization schemes

The simulation models of the NPS and RCS schemes are obvious (see Appendix 4). For the QPS, a maximum possible queueing time is used to ensure that the radio quality at the end of the queueing period, with a high probability, is still good enough to perform a handover. This maximum queueing time is given by the time interval the MS spends in the handover area (degradation interval). It is obvious that the performance of the QPS is enhanced for a longer degradation interval, that is, a longer maximum queueing time (simulation results will show it). In microcellular environments there is more overlap of cell coverage areas than that which exists for mobile networks with macrocells; this is because they have been engineered for higher coverage probability [42]. Then, as the cell under study has been chosen to be a microcell, the performacne of the QPS is going to be even higher. Moreover, only a finite queue length is allowed in order to avoid very large queue sizes, although a natural boundary of the queue size is implicit because of the incessantly queue departures due to either handovers being served or expiration of the maximum possible queueing time.

It is accepted that once the handover request is issued, the power that the MS receives from the current BTS will monotonically degrade [33]. The rate of degradation, and hence the maximum tolerable degradation interval, depends on the velocity of the MS. A truncated normal distribution for the velocity has been considered in the previous section, so normally distributed degradation intervals are considered, as in [33]. Exponentially distributed degradation intervals have been considered in other works [32][34]. The overlapped area between microcell coverage areas can be very different depending on several factors [42]. In this Thesis a minimum value for the overlapped area equal to 50m (one-sixteenth of the R_{micro}) is considered, which implies theat the simulation results for the QPS will be obtained for the worst case situation (smallest overlapped area). Therefore, the maximum tolerable degradation interval (T_{di}) associated with each MS entering the handover area for a R_{micro} = 800m is drawn from a normal distribution with a mean of $\overline{T}_{di} = 6$ seconds and a standard deviation of 4 seconds.

6.2.4. Evaluation criteria

The *GoS* refers to the degree of call blocking, and is a basic measure of the teletraffic performance of a cellular system from the user's point of view. While the user may tolerate some degradation in the voice quality (half-rate channels, fast fading, etc), the frequent blocking of calls is annoying and frustrating. The GoS can be defined as a combination of the following probabilities: probability of blocking on the RACH (P_{nbac}), probability of new call blocking (P_{nb}), probability of fixed network blocking (P_{bfix}) –when mobile-to-fixed calls–, probability of handover failure (P_{hf}) and probability of forced termination (P_{fct}). Therefore, the GoS can be considered as the fraction of calls which are blocked at any stage, and it may be expressed as

$$\begin{aligned} GoS = P_{nbac} + (1 - P_{nbac}) \times P_{nb} + (1 - P_{nbac}) \times (1 - P_{nb}) \times P_{bfix} + \\ + (1 - P_{nbac}) \times (1 - P_{nb}) \times (1 - P_{bfix}) \times P_{fct} \end{aligned} \tag{6}$$

In this Thesis the main performance parameters which are considered in order to measure the GoS of existing GSM services (for the cell under consideration) are:

- *Probability of new call blocking*, P_{nb} , is the probability that a new call attempt cannot be served due to the lack of free channels.
- *Probability of handover failure*, P_{hf} , is the probability that an incoming handover request cannot be satisfied because of the unavailability of channels, and thus results in a termination of the call.

From the network's point of view, two important parameters are:

- *Network capacity*, which is evaluated by means of the *total carried traffic*, A_{carr} . The carried traffic is the amount of traffic admitted to the cellular network as opposed to the offered traffic, and it indicates the average number of busy channels (ongoing calls) at any one time in the cell. A_{carr} can be easily evaluated once P_{nb} and P_{hf} are determined by

$$A_{carr}(Erlangs) = A_n \times (1 - P_{nb}) + A_h \times (1 - P_{hf}) \tag{7}$$

- C*hannel utilization*, U_{ch}, which is a normalization of the A_{carr}, is the percentage of the overall simulation time that a specific channel is being used. This parameter is usually given as the average channel utilization of several channels.

These performance parameters are evaluated as a function of the total offered traffic load. Furthermore, it is assumed that the GSM network is operating at a maximum blocking probability of 2% for existing GSM services (P_{nb} = P_{hf} = 2%); this means that the cell has been engineered at 2% blocking probability for the mean offered load in the rush hour (worst case situation) [42]. By evaluating all these performance parameters, the performance of the network with a specific handover priority-based channel allocation scheme can be fully evaluated for different values of channels exclusively reserved to GPRS (N_{gprs}).

Other performance parameters have been also obtained during the simulations to measure special features of every channel allocation scheme used, but they have not been considered in the results. An example of the performance parameters obtained in a simulation run is shown in Appendix 3.

6.3. Simulation model

There are three types of **events** in the simulation: the arrival events for new call arrivals and handover requests (*CallArrival*), the request events for allocating a channel for a call

(*ChannelRequest*), and the completion events for a call releasing a channel (*ChannelCompletion*). The events are mainly characterized by four parameters:

- ev_type: type of the event (how the event is to be handled).
- ev_time: time of occurrence of the event (when the event is to be handled).
- ev_to: event handler which must manage the event.
- ev_job: standard job object carried by the event

Every event carries a **job**, which indicates the kind of handling the system performs with the event. The most important parameters of the jobs are:

- job_type: type of the job.
- job_in: time when the job enters the system (the job enters in the BTS_server).
- job_start: time when the job begins to be served (a channel is allocated for the job).
- job_out: time when the job leaves the system (the channel is released).

There are two types of jobs, jobs for calls (*JobCall*) and jobs for handovers (*JobHandover*). The simulator could be easily extended to work with GPRS traffic by defining a new job for GPRS connections and the way to handle this new job in every “block” of the system.

The events are inserted into an **Event List** and are arranged in order depending on the time of occurrence of the event –ev_time– (at the head of the list the most inminent event). This event list is managed by the **Event Scheduler**, which is the core of the simulation program. The event scheduler is always executed before an event, and is responsible of sending the events to the appropriate **Event Handler** depending on the parameter ev_to. It is also responsible of checking if the stopping condition is fulfilled, and then ending the simulation. There are two event handlers in the simulator: the **Traffic_Generator** and the **BTS_Server**. The traffic_generator is responsible of generating the new call arrivals and handover requests according to the traffic models explained in section 6.1.2. The BTS_server manages the events *ChannelRequest* and *ChannelCompletion* and is responsible of the radio resource allocation management and the data collection to evaluate the performance parameters. There are specific routines to handle the events depending on the event type, the job type and the channel allocation scheme. A simulation clock is maintained in the event scheduler to indicate the progress of the simulation. The clock value is the timestamp of the event being processed –ev_time–.

The traffic_generator counts the total number of new call arrivals, N_n , and the number of handover requests, N_h. The BTS_server counts the number of blocked calls, N_{nb} , and the number of handover failures, N_{hf} . A simulation iteration terminates when the stopping condition is fulfilled. The stopping condition for every simulation run is $N_n = 400.000$, which means that 400.000 new call requests are simulated. A “high value” is chosen to ensure that the simulation results are stable (transient removal by very long run and proper initialization). There could be an alternative stopping condition by fixing a maximum simulated time.

The simulation first performs the paramater initialization: parameters as N_{trx}, N_{ch}, N_{sig}, N_{gprs}, N_{shared}, N_{ho}, N_{com}, A_{off}, f_{ho}, μ_{ch}, μ_{cd}, N_n,… are chosen depending on the objective of every simulation run. Then, two first *CallArrival* events are generated, one for a new call arrival (*JobCall*) and the other one for a handover request (*JobHandover*). The event generation is completed in the following steps:

1. Allocate the storage for the event.
2. Determine the type of the event (*CallArrival*, *ChannelRequest*, *ChannelCompletion*) and the type of job which it carries (either *JobCall* or *JobHandover*).
3. Handle the event by executing the specific routine depending on the event type, job type and channel allocation scheme chosen.
4. Generate the new event/s (if necessary) and determine the timestamp of it/them (ev_time).
5. Insert the new event/s into the event list.

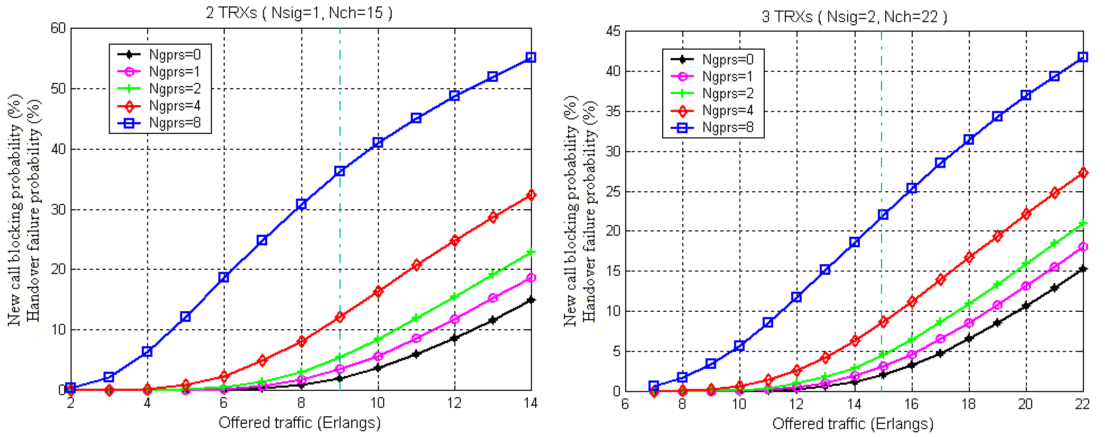
The events are processed in order depending on the value of ev_time: the next event to process is deleted from the event list and is processed by the corresponding event handler based on the ev_to parameter. For a *CallArrival* event of a *JobCall*, if $N_n = 400.000$ then the simulation iteration terminates and performance parameters are computed:

$$P_n = \frac{N_{nb}}{N_n} \quad (8), \qquad P_h = \frac{N_{hf}}{N_h} \quad (9), \qquad A_{carr} \text{ from (5) and (7)}$$

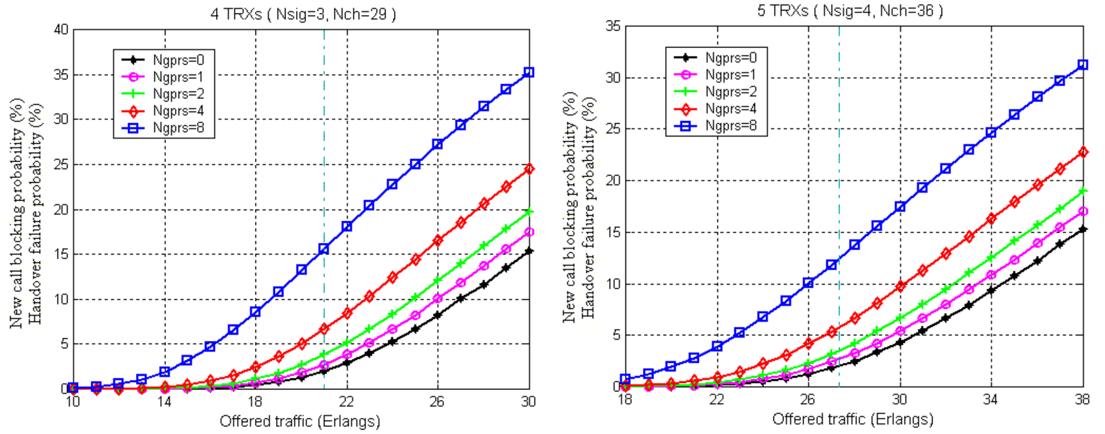
Otherwise, a new iteration is conduced. The general structure of the simulation model and detailed flow charts of every structural element of the simulation are given in Appendix 4.

6.4. Simulation results, discussion and interpretation

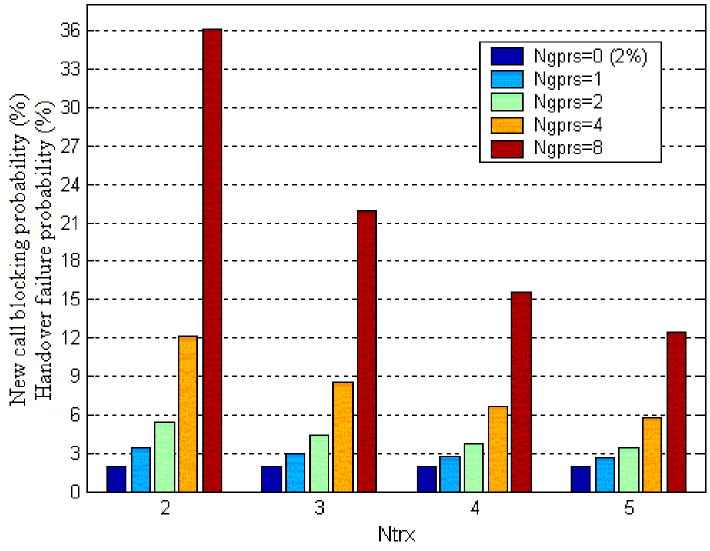
Our objective is to investigate how the capacity of existing GSM services is affected by the GPRS PS implementation into the GSM network. Depending on the GPRS penetration factor, N_{gprs} should change in order to guarantee appropiate QoS for GPRS users [8]. As the number of GPRS subscribers grows, GPRS traffic load is harder to estimate; in lack of realistic traffic distribution profiles for GPRS, the GPRS offered traffic load can be simplified to be



a) P_{nb} and P_{hf} versus A_{off} for $N_{trx} = 2$ when ↑N_{gprs} b) P_{nb} and P_{hf} versus A_{off} for $N_{trx} = 3$ when ↑N_{gprs}



c) P_{nb} and P_{hf} versus A_{off} for $N_{trx} = 4$ when ↑N_{gprs} d) P_{nb} and P_{hf} versus A_{off} for $N_{trx} = 5$ when ↑N_{gprs}



e) P_{nb} and P_{hf} versus N_{trx} for A_{off} ($P_{nb\,,\,hf} = 2\%$) when ↑N_{gprs}

Figure 6.2. Effects of increasing N_{gprs} on GSM capacity (P_{nb} and P_{hf}) for different values of N_{trx}

proportional to the growth of subscriber numbers. Then, simulations are performed for different values of N_{gprs} and the effects of an increasing value of N_{gprs} on capacity of existing GSM services are computed. As the first generation of GPRS mobile phones use multi-slot configurations 1:2 and 1:4 [14], values of $N_{gprs} = 1, 2, 4 ,6$ and 8 are considered. $N_{gprs} = 0$ means that measured parameters are referred to GSM without GPRS PS implementation yet (or CS implementation).

Before studying the basic microcell scenario with $N_{trx} = 4$, the effects of GPRS PS implementation on a cell with different number of TRXs (carriers) are computed in order to have a general vision of the GPRS impacts on a generic GSM network. Figure 6.2 shows how the value of N_{gprs} impacts the capacity of existing GSM services (parameters P_{nb} and P_{hf}) for different values of N_{trx}. The NPS is used, that is, new calls and handovers are handled without preference, and P_{nb} and P_{hf} have the same value, which can be theoretically calculated by equation (1). Figures 6.2.(a)-(d) show clearly that in the fourth cases P_{nb} (P_{hf}) increases when more N_{gprs} channels are exclusively reserved for GPRS services. This increase is higher when less TRXs (N_{trx}) are available in the cell, because a higher proportion of the N_{ch} available channels are taken for GPRS (value of N_{gprs}/N_{ch} increases). Figure 6.2.(e) shows the same results when the cell offered load has been engineered at a maximum 2% blocking probability (worst case situation) for the four cases of N_{trx}. It can be noted that the more TRXs a cell has, the less the packet data traffic tends to affect the GSM traffic. Moreover, a higher number of TRXs per cell will facilitate more resources for GPRS traffic (unused GSM capacity will be higher) and it is also beneficial to remember that capacity enhancement techniques such as frequency hopping require several TRXs per cell. It can be observed that with only 2 or 3 TRXs per cell, N_{gprs} should be less than 2 or GPRS CS implementation should be considered (packet data services just using the unused GSM capacity).

6.4.1. Basic microcell scenario

The basic microcell scenario consists on a microcell with $N_{trx} = 4$, as explained in section 6.2.1. Table 6.1 summarizes the system parameters that refer to this basic microcell scenario (additional values are given within brackets); when the used values differ from those of the basic scenario, this will be explicitly indicated in the figure caption.

Figure 6.3 shows the channel utilization in the microcell (GPRS is not implemented yet). It is well known that even at peak GSM traffic load the average utilization of traffic channels is not very high because of statistical traffic fluctuations [45]. This can be clearly seen in the figure; for instance, when the cell offered load causes a 2% blocking probability (worst case situation), the channel utilization is 71,07%, so 28,93% is idle time which can be used by other services. Therefore, due to bursty nature of GPRS applications, it is a wastage of radio resources if GPRS data traffic is not allowed to use any of these idle traffic channels. That is the main reason why allocating new spectrum for GPRS services is not considered, as seen in section 3.2.

Model	Parameter	Value
Network model	Cell radius, R_{micro}	800 m
	Number of TRXs, N_{trx}	4
	Total number of channels available in the cell, N_t	32
	Number of signalling channels, N_{sig}	3
	Number of traffic channels, N_{ch}	29
	Number of channels reserved for GPRS, N_{gprs}	0 (1,2,4,6,8)
	Number of channels reserved for handover, N_{ho} (RCS)	0 (1,2,3,4,6)
	Number of channels for sub-rating, N_{sub} (SRS)	0 (1,2,3,4,6)
Mobility model	Average call duration time, $1/\mu_{cd}$	120 sec
	Average velocity	30 km/h
	Standard deviation of velocity	20 km/h
	Average channel holding time, $1/\mu_{ch}$	60 sec
	Mean degradation interval (QPS)	6 (8) sec
	Standard deviation of degradation interval (QPS)	4 (5.3) sec
Traffic model	Total offered load, A_{off}	var
	New call arrival rate, λ_n	var
	Handover arrival rate, λ_h	var
	Percentage of handover traffic over A_{off}, f_{ho}	35%

Table 6.1. System parameters for the basic microcell scenario

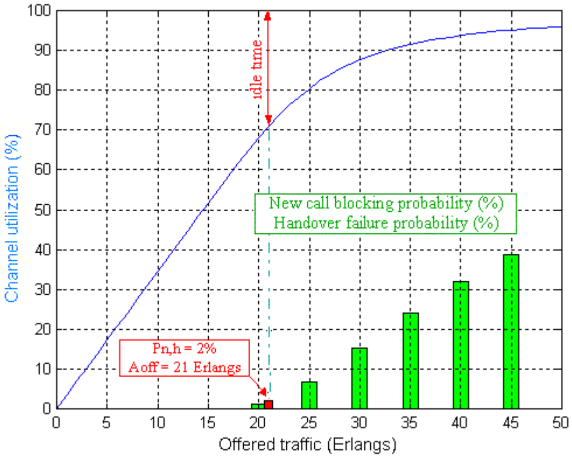
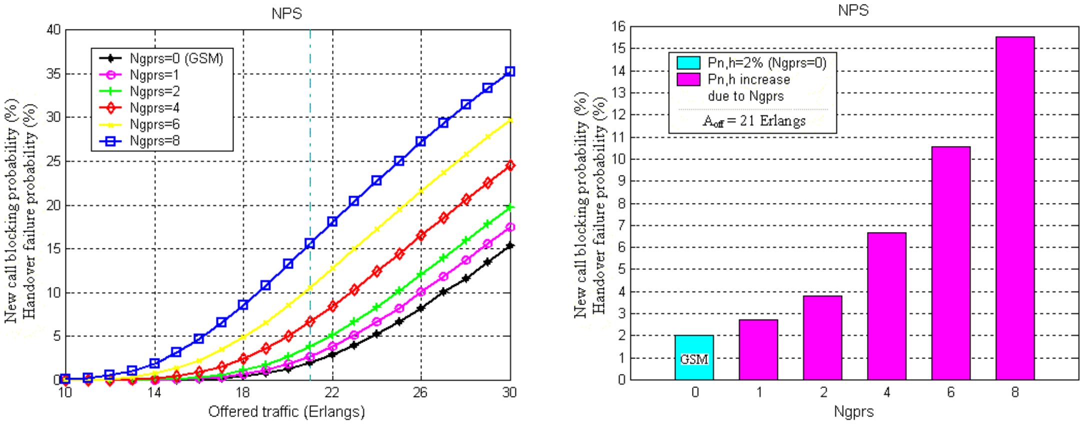
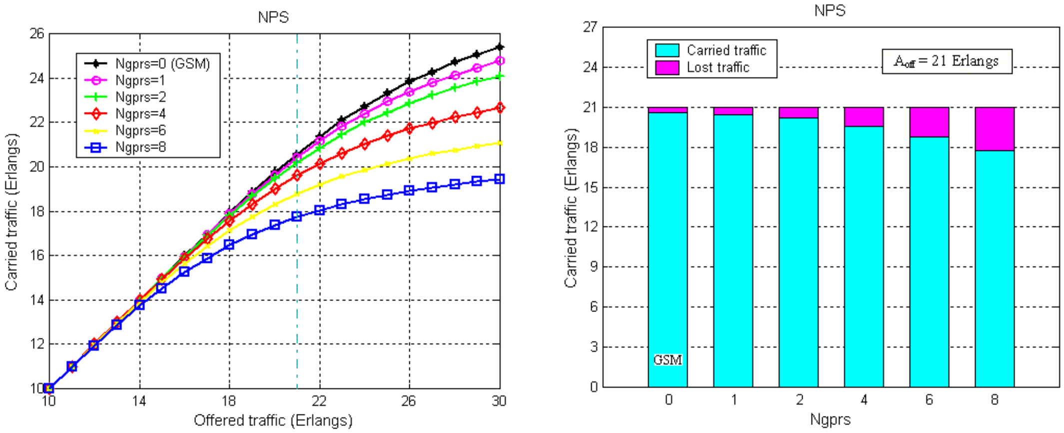


Figure 6.3. Channel utilization in GSM

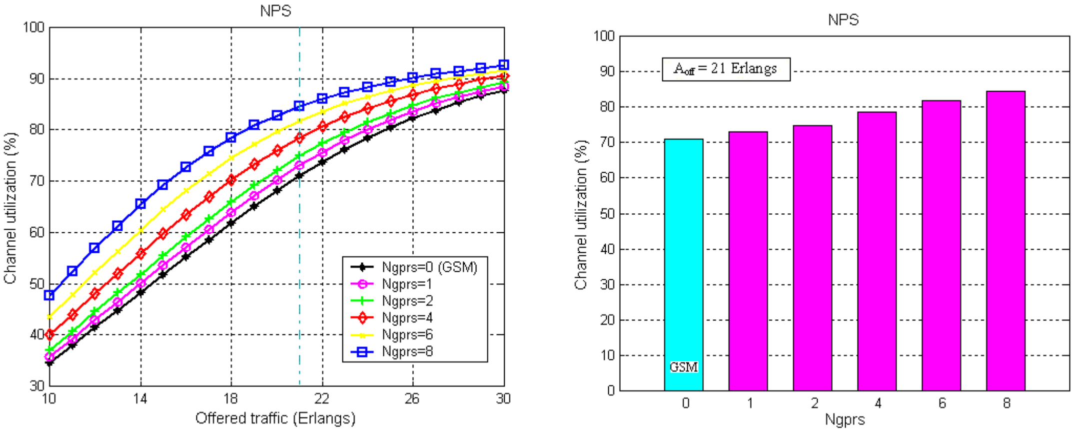
Figure 6.4 shows the effects of increasing N_{gprs} on capacity of existing GSM services when the NPS is used. From figure 6.4.(a), one can clearly see that the more N_{gprs} channels a cell reserves, the more P_{hf} and P_{nb} are increased at any specific value of offered load and,



a) P_{nb} and P_{hf} versus A_{off} when ↑N_{gprs} b) P_{nb} and P_{hf} versus N_{gprs} for $A_{off} = 21$Erl.



c) A_{carr} versus A_{off} when ↑N_{gprs} d) A_{carr} versus N_{gprs} for $A_{off} = 21$Erl.



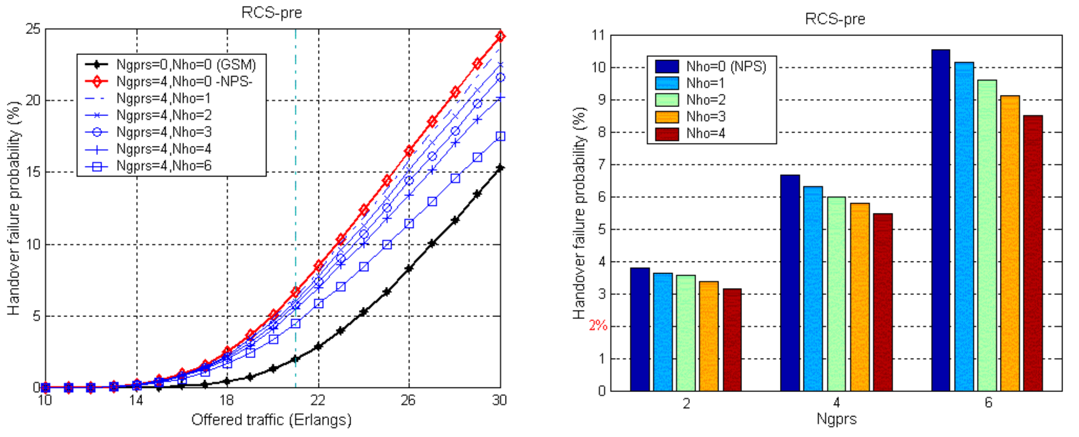
e) U_{ch} versus A_{off} when ↑N_{gprs} f) U_{ch} versus N_{gprs} for $A_{off} = 21$Erl.

Figure 6.4. Effects of increasing N_{gprs} on GSM capacity for the non-prioritized scheme

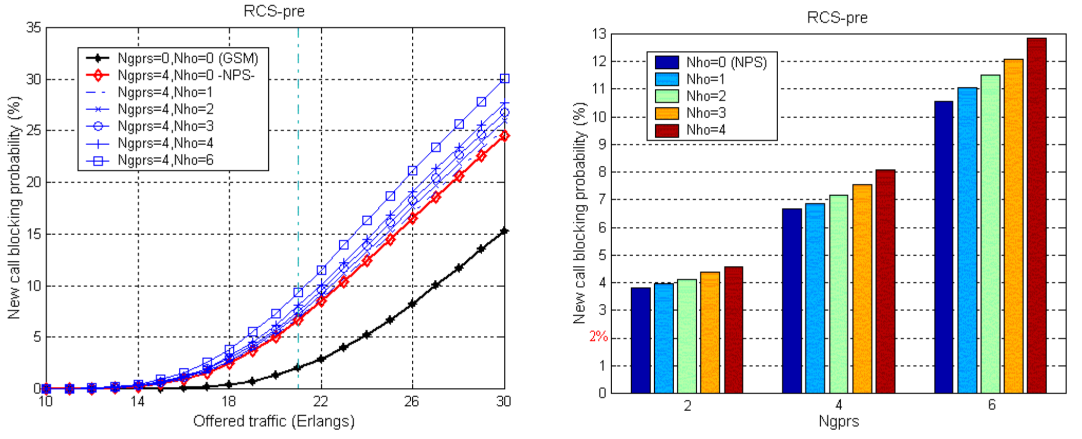
consequently, the less GSM traffic is carried as shown in figure 6.4.(c). As both P_{hf} and P_{nb} are equal because no priority is given to handovers over new calls, the increase in both probabilities due to N_{gprs} is also the same. Moreover, the channel utilization is increased as more N_{gprs} channels are exclusively reserved for GPRS, as shown in figure 6.4.(e), which means that less unused GSM capacity is available for GPRS services using the shared channel pool. Figures 6.4.(b)(d)(f) show the same results when the cell offered load causes a 2% blocking probability (worst case situation). From figure 6.4.(b), it can be observed that values of P_{hf}, P_{nb} rise unacceptable levels when N_{gprs} exceeds 4 (more than 10%). Therefore, installing a new TRX in the cell should be considered in case of requiring more than $N_{gprs} = 4$ channels (e.g., due to a high growth of GPRS subscribers number), in order to keep up with the quality demands of GPRS users. When $N_{gprs} = 1$ and 2, the increase in P_{hf}, P_{nb} (from 2% to 2.74% and 3.82% respectively) is almost negligible compared to the benefit of reserving additional PDCHs for GPRS users [8], besides taking into account that figures 6.4.(b)(d)(f) are referred to the worst case situation, which means that actual values of P_{hf}, P_{nb} would be even smaller. When $N_{gprs} = 4$, the increase in P_{hf}, P_{nb} is considerable (from 2% to 6.68%), especially regarding P_{hf} because of its relative importance over P_{nb}, as explained in section 5.2.1. But in this case there is the possibility of decreasing P_{hf} using the handover prioritization schemes studied before instead of the NPS used here.

Figure 6.5 shows the performance characteristics (P_{hf}, P_{nb}, A_{carr}, U_{ch}) for the existing GSM services in the microcell when $N_{gprs} = 4$ and the reserved channel scheme with pre-reservation is used. In each of these curves, the performance for the NPS with $N_{gprs} = 4$ and with $N_{gprs} = 0$ (not GPRS PS implementation yet) is incorporated for comparison purposes. From figure 6.5.(a), it can be noted that P_{hf} is decreased as more N_{ho} channels are exclusively reserved for handover requests, and consequently P_{nb} must be increased as shown in figure 6.5.(c). Figures 6.5.(e)(f) show that A_{carr} and U_{ch} are hardly degraded when compared to the nonpriority case.

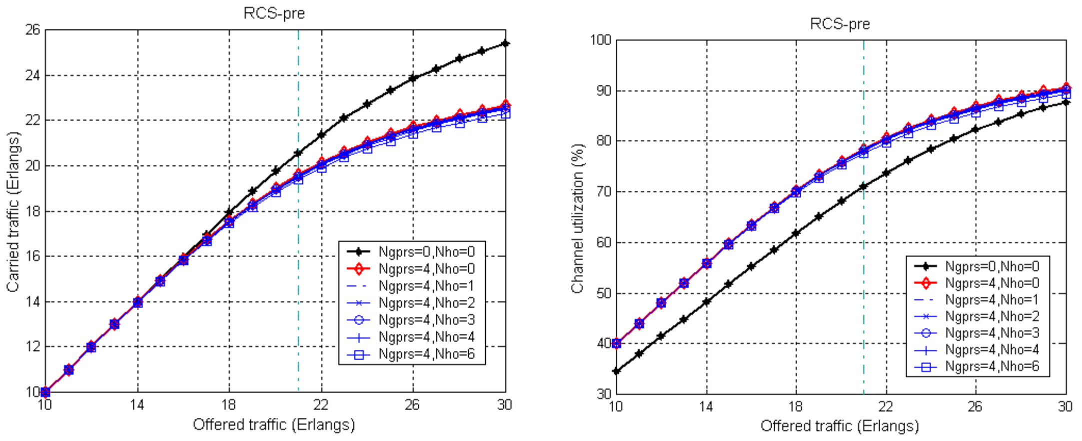
Figure 6.6 shows the same performance characteristics as figure 6.5 but for the reserved channel scheme with post-reservation. It can be observed from figures 6.6.(a)(c) that the decrease in P_{hf} and the increase in P_{nb} is higher than those in the pre-reservation. Moreover, with $N_{ho} \geq 3$, the value of P_{hf} can be even reduced beneath the value obtained in GSM for the NPS. However, figures 6.6.(e)(f) indicate that A_{carr} and U_{ch} are slightly degraded when compared to the pre-reservation case, so the reduction compared to the nonpriority case is higher.



a) P_{hf} versus A_{off} for N_{gprs}=4 when ↑N_{ho} b) P_{hf} versus N_{gprs} for A_{off} = 21Erl. when ↑N_{ho}

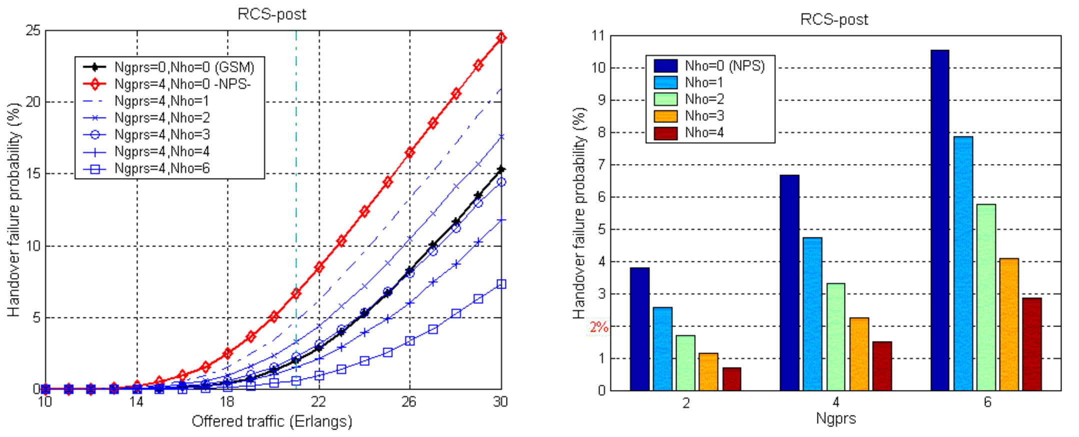


c) P_{nb} versus A_{off} for N_{gprs}=4 when ↑N_{ho} d) P_{nb} versus N_{gprs} for A_{off} = 21Erl. when ↑N_{ho}

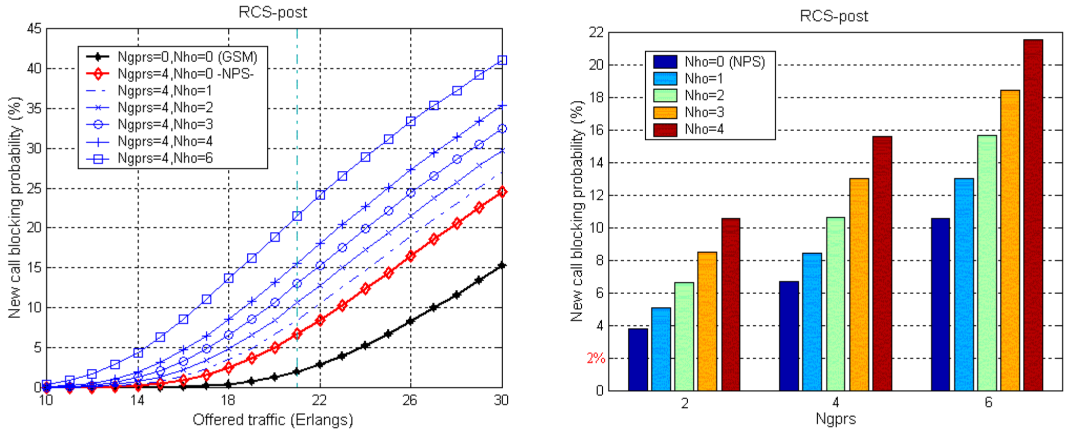


e) A_{carr} versus A_{off} for N_{gprs}=4 when ↑N_{ho} f) U_{ch} versus A_{off} for N_{gprs}=4 when ↑N_{ho}

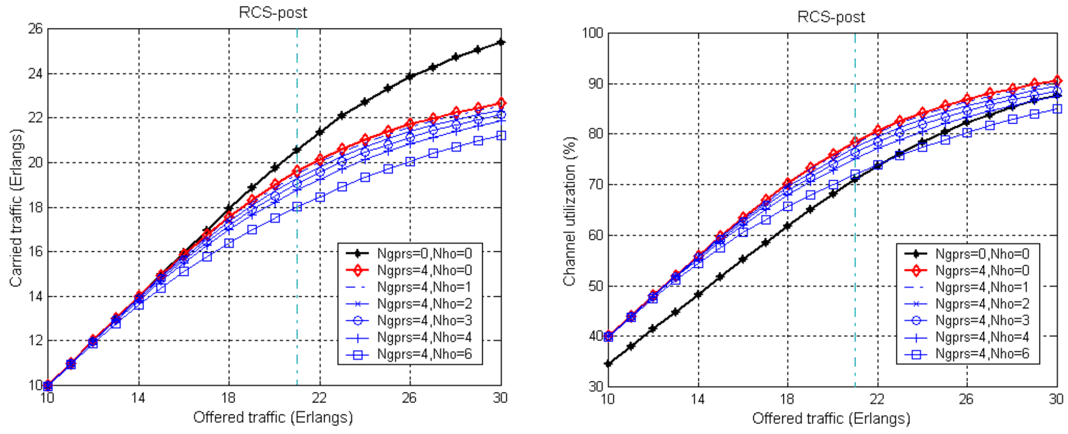
Figure 6.5. GSM performance parameters for the reserved channel scheme with pre-reservation



a) P_{hf} versus A_{off} for N_{gprs}=4 when ↑N_{ho} b) P_{hf} versus N_{gprs} for A_{off} = 21Erl. when ↑N_{ho}



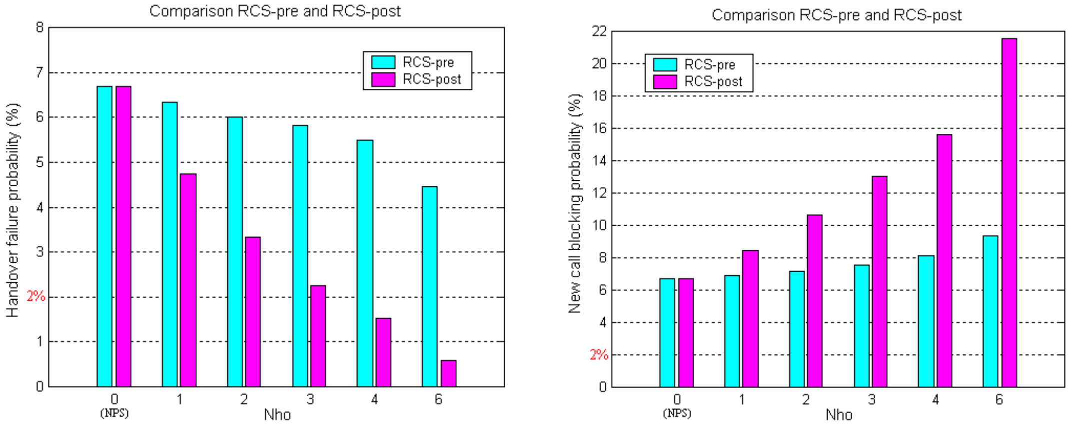
c) P_{nb} versus A_{off} for N_{gprs}=4 when ↑N_{ho} d) P_{nb} versus N_{gprs} for A_{off} = 21Erl. when ↑N_{ho}



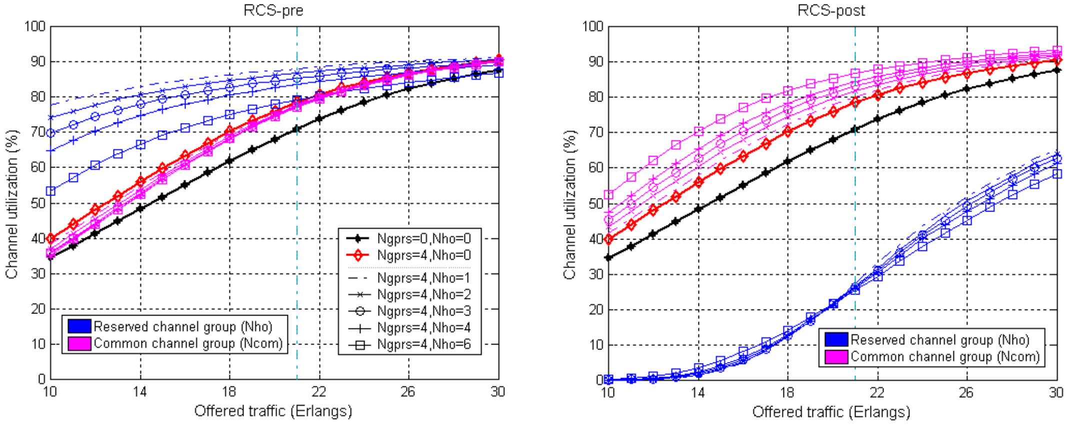
e) A_{carr} versus A_{off} for N_{gprs}=4 when ↑N_{ho} f) U_{ch} versus A_{off} for N_{gprs}=4 when ↑N_{ho}

Figure 6.6. GSM performance parameters for the reserved channel scheme with post-reservation

Figures 6.7.(a)(b) compare both RCSs when the cell offered load equals 21 Erlangs, which implies a blocking probability of 2% (worst case situation) in the case of the GSM network operating without GPRS PS implementation yet. It can be observed that the performance of RCS-post as far as P_{hf} is concerned is better than RCS-pre, although as far as P_{nb} is concerned is on the contrary. Such an observed result is of no surprise because in RCS-post, since the handover requests always look at the common channel group (N_{com}) first for handover purposes, there are many instances where handovers occupy a channel from N_{com} even when there are some free channels available in the reserved channel group (N_{ho}). This means that the channel utilization for the reserved channel group (N_{ho}) in the case of RCS-post will be much less than that for the RCS-pre, as can be seen in figures 6.7.(c)(d).

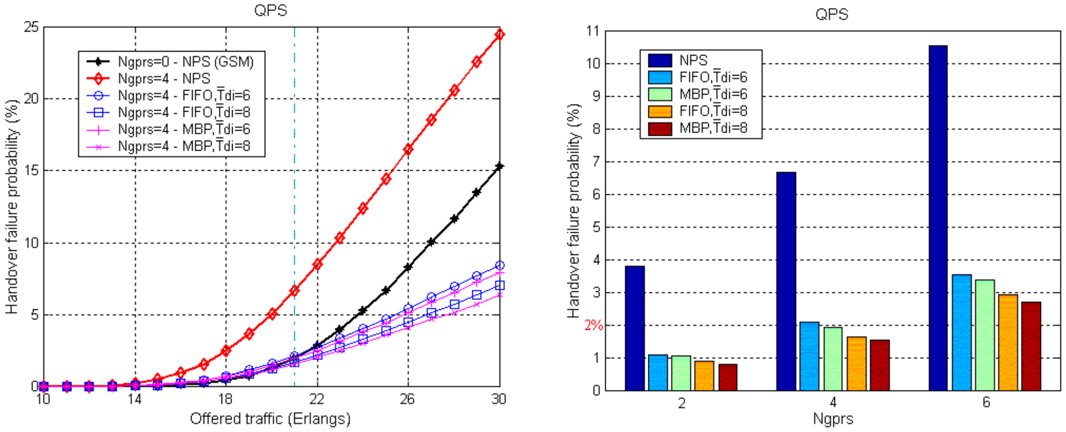


a) P_{hf} versus N_{ho} for $A_{off} = 21$Erl. and $N_{gprs}= 4$ b) P_{nb} versus N_{ho} for $A_{off} = 21$Erl. and $N_{gprs}= 4$

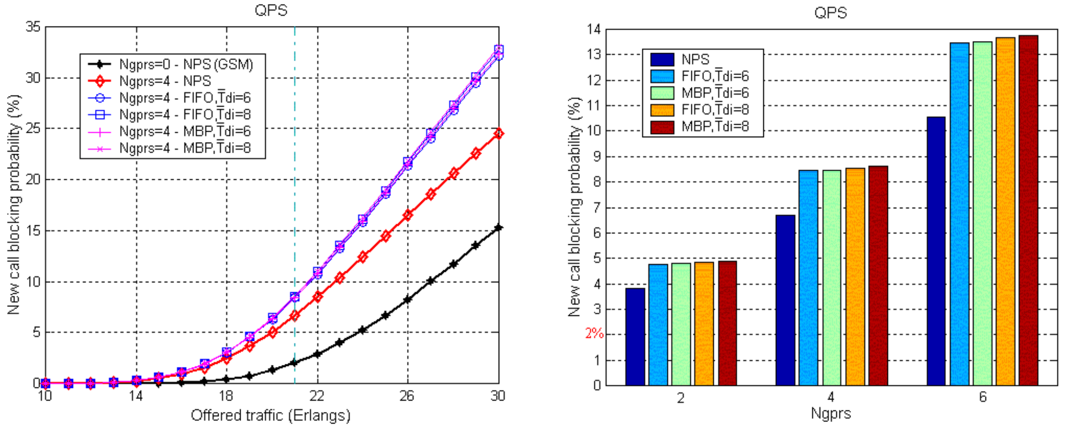


c) U_{ch} versus A_{off} for N_{gprs}=4 when ↑N_{ho} d) U_{ch} versus A_{off} for N_{gprs}=4 when ↑N_{ho}

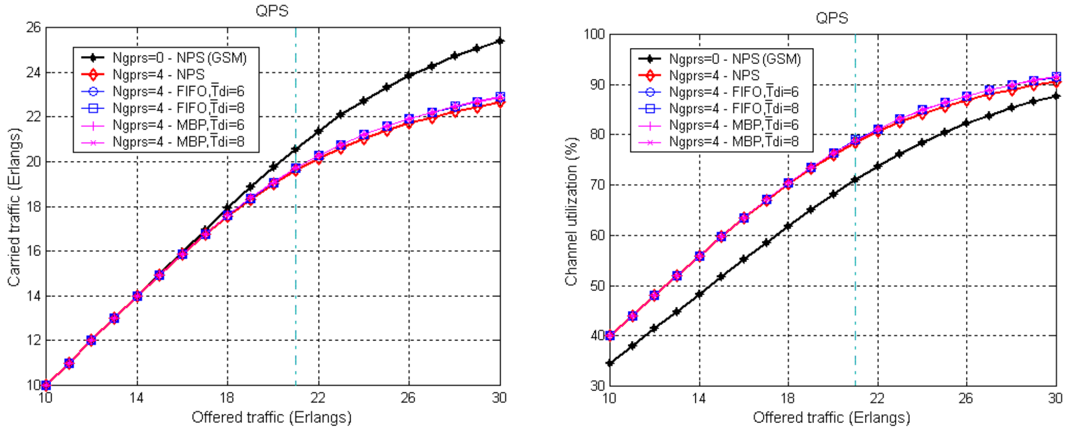
Figure 6.7. Comparison between RCS schemes: pre-reservation and post-reservation



a) P_{hf} versus A_{off} for N_{gprs}=4 b) P_{hf} for A_{off} = 21Erl. versus N_{gprs}



c) P_{nb} versus A_{off} for N_{gprs}=4 d) P_{nb} for A_{off} = 21Erl. versus N_{gprs}

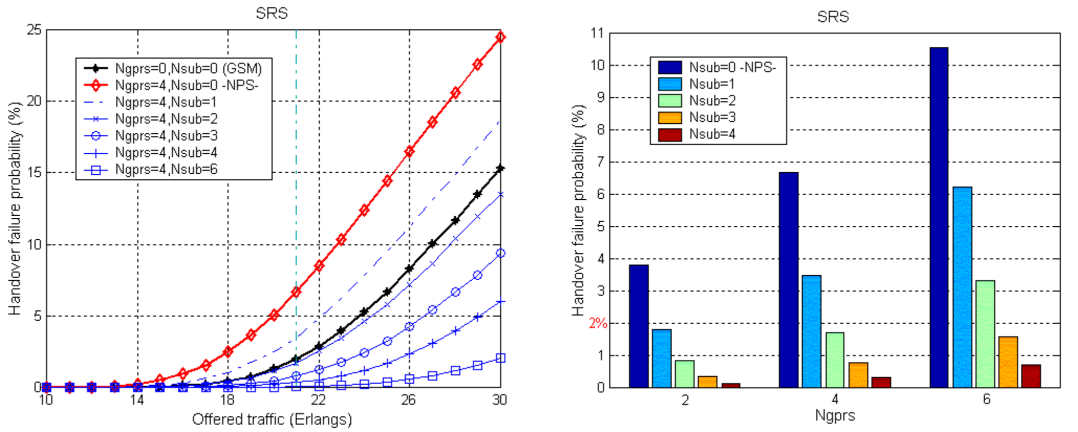


e) A_{carr} versus A_{off} for N_{gprs}=4 f) U_{ch} versus A_{off} for N_{gprs}=4

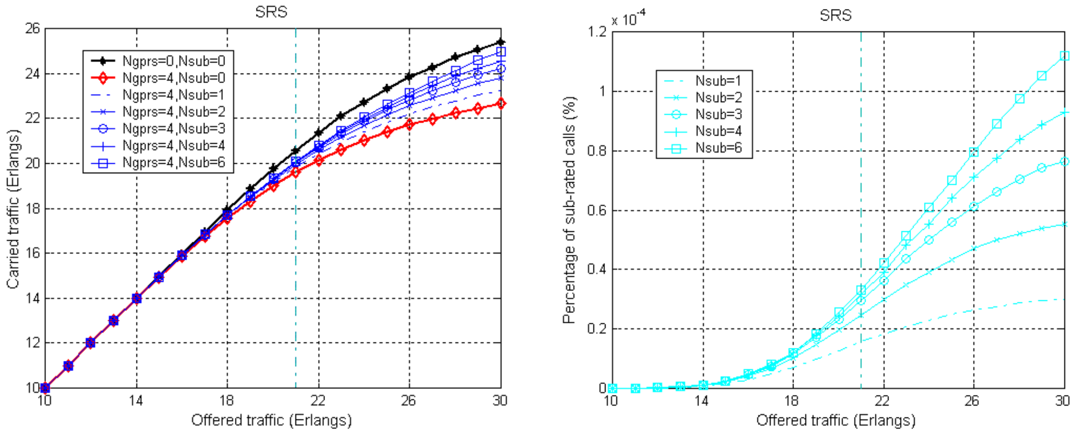
Figure 6.8. GSM performance parameters for the queueing priority scheme: FIFO and measurement-based priority (MBP)

Figure 6.8 shows the performance characteristics (P_{hf}, P_{nb}, A_{carr}, U_{ch}) for the existing GSM services in the microcell when $N_{gprs} = 4$ and the queueing priority scheme is used. In each of these curves, the performance for the NPS with $N_{gprs} = 4$ and with $N_{gprs} = 0$ (not GPRS PS implementation yet) is incorporated for comparison purposes. Two QPSs are studied: the FIFO scheme and the MBP scheme, and two possible degradation intervals are considered (see table 6.1) for comparison purposes. In [33], Tekinay and Jabbari's conclusion is that both P_{hf} and P_{nb} for the MBP scheme are always smaller than that of FIFO scheme. However, this cannot be true: since the channels available in the system are the same for both FIFO and MBP schemes (a fixed frequency assignment strategy has been considered), a smaller P_{hf} means that most handovers are accommodated (and more channels are occupied by handovers) and, consequently, fewer idle channels are available for new calls, which compulsory results in a large P_{nb}. Figure 6.8.(a) indicates that P_{hf} for MBP scheme is smaller than for FIFO scheme, but the difference is negligible. P_{nb} for FIFO is smaller than for MBP, though not discernible from figure 6.8.(c) (see figure 6.8.(d)). Furthermore, figure 6.8.(a) shows that the achieved value of P_{hf} in both schemes is beneath the value obtained in GSM for the NPS. From figure 6.8.(a), it can also be noted that the handover performance of both QPSs is better for a longer degradation interval, as said in section 6.2.3. Figures 6.8.(e)(f) indicate that A_{carr} and U_{ch} for both QPSs are almost identical and are slightly upgraded when compared to the nonpriority case, in contrast to the RCS.

Figure 6.9 shows the performance characteristics (P_{hf}, A_{carr}) for the existing GSM services in the microcell when $N_{gprs} = 4$ and the sub-rating scheme is used. As P_{nb} is not degraded when using this handover prioritization scheme, its curve is not shown. In [35], it is assumed that every channel from the N_{shared} shared pool can be sub-rated, but in this Thesis it is considered that just N_{sub} channels out of the N_{shared} channels can be used for sub-rating. Figure 6.9.(a) shows that P_{hf} heavily decreases as N_{sub} increases. With only $N_{sub} > 1$, the value of P_{hf} can be even reduced beneath the value obtained in GSM for the NPS. From figure 6.9.(c), it can be noted that the SRS effectively increases the carried traffic when compared to the nonpriority case, because P_{hf} has been decreased without degrading P_{nb}, unlike the other handover prioritization schemes evaluated. Since voice quality for a sub-rated channel may not be as good as for a full-rate channel, it is important to study how SRS affects voice quality. Figure 6.9.(d) plots the percentage of sub-rated calls over the total calls carried by the cell. It can be observed that even with high offered load this percentage is very small. More "costs" of this scheme regarding the reduction of voice quality are widely studied in [35].



a) P_{hf} versus A_{off} for N_{gprs}=4 when ↑N_{sub} b) P_{hf} for A_{off} = 21Erl. versus N_{gprs} when ↑N_{sub}



c) A_{carr} versus A_{off} for N_{gprs}=4 when ↑N_{sub} d) Percentage of sub-rated calls versus A_{off}

Figure 6.9. GSM performance parameters for the sub-rating scheme

6.4.2. Overlaid macrocell/microcell scenario

In the previous section the handover performance in the microcell under study has been improved by using several handover prioritization schemes, but at the expense of some increase in the new call blocking probability, which in some cases, as in the RCS-post, rose unacceptable levels (see figures 6.6.(c)(d)). One way of improving the handover performance at the same time that obtaining a P_{nb} smaller than in the basic microcell scenario would be overlaying a macrocell in the area where the microcell is located. Current GSM networks consist of multiple layers of cells (HCS) with different cell sizes with the aim of offering complete coverage and sufficient capacity [42]. Therefore, the overall teletraffic performance of the basic microcell scenario can be enhanced by having an umbrella macrocell overlaid to a microcellular cluster, where our cell under study (target cell) is located.

In order to relax the need for fast handovers between the cells belonging to the microcellular cluster, the traffic from the fast-moving mobiles can be carried by the umbrella macrocell, hence reducing the number of handovers in the cluster. This improves the overall network performance because handovers increase signaling traffic, and back and forth bouncing may cause capacity problems in the signaling channels, which create constraints. As said in section 6.2.2, a normal distributed speed with mean $\overline{V} = 30$ km/h and standard deviation equal to 20km/h and truncated at [0,100]km/h has been considered for the mobiles (see figure 6.10). A threshold for the velocity equal to 50km/h is considered for the slow-moving mobiles (see figure 6.10), which means that an incoming handover request to the target microcell whose velocity exceeds 50km/h is powered up and assigned a channel from the macrocell BTS, assuming that a macrocell channel is available.

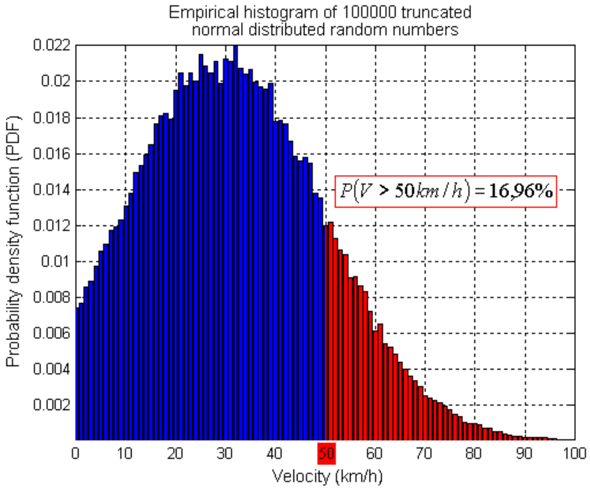


Figure 6.10. PDF of velocity for the mobiles

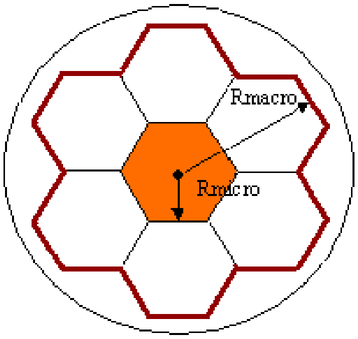
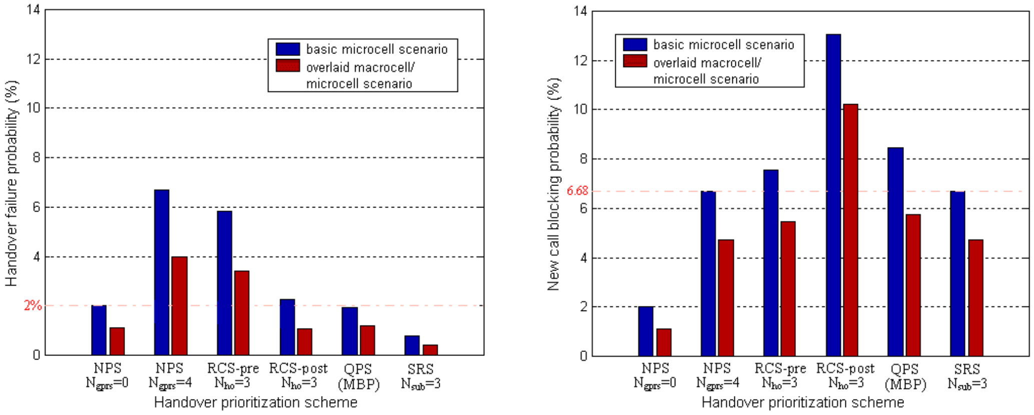


Figure 6.11. Overlaid macrocell/ microcell scenario

A macrocell overlaying 7 microcells is considered, one of them being the target microcell under study and located in the middle of the other 6 as indicated in figure 6.11. The cell radius of the macrocell is then $R_{macro} = 3xR_{micro} = 2400$m, so the mean channel holding time in the macrocell is $\overline{T}_{ch} = 90$ seconds [44]. The target microcell is supposed to be operating at a maximum 2% blocking probability (worst case situation), which is achieved when $A_{off} = 21$ Erlangs. As $f_{ho} = 0.35$, then from equation (5) it can be obtained $A_h = 7.35$ Erlangs. Considering that $P(V > 50km/h) \approx 17\%$ (see figure 6.10), then the offered traffic from the target microcell to the umbrella macrocell will be 1.25 Erlangs approximately. The 6 surrounding microcells are supposed to generate 2 Erlang of traffic to the umbrella macrocell, so the total offered traffic from the whole microcellular cluster to the macrocell is 13.25 Erlangs. In order to carry with this traffic with a low level of blocking rate, the macrocell is considered to have 3 TRXs. Then 24 physical channels are available, and if 2 of them are reserved for network signaling, 22 traffic channels are available to serve the cluster. Using equation (1), with C=22 and A_{off} = 13.25 Erlangs, the blocking probability equals 0.72%, so the “hand up” handover traffic from the target microcell will be carried properly.

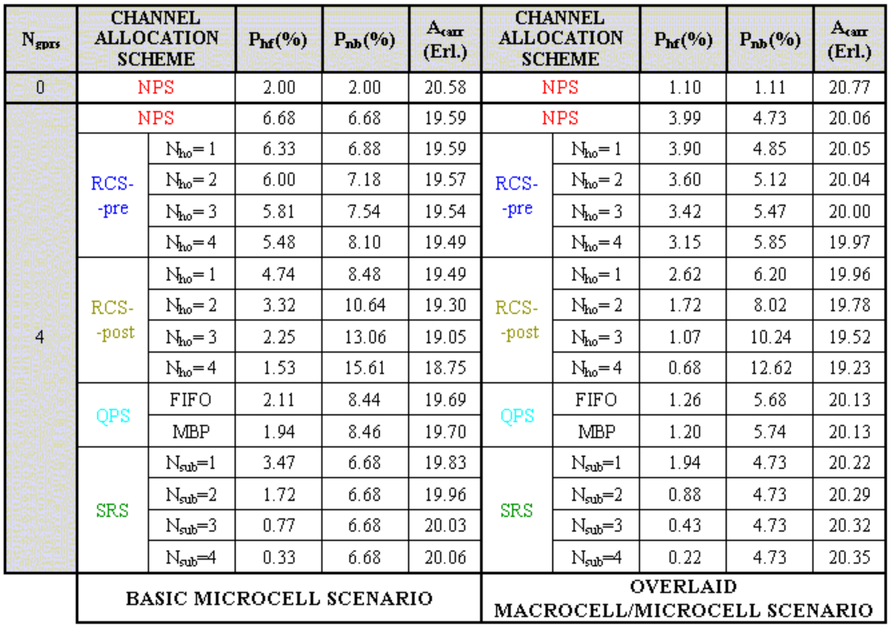


a) P_{hf} for A_{off} = 21Erl. when N_{gprs}= 4 b) P_{nb} for A_{off} = 21Erl. when N_{gprs}= 4

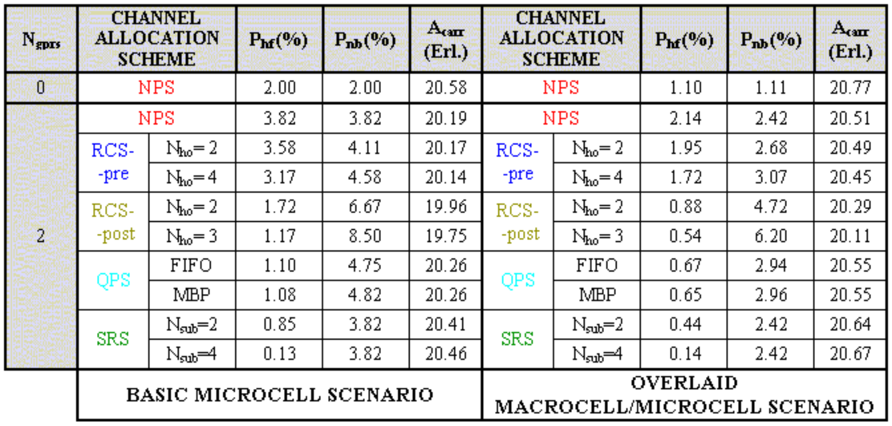
Figure 6.12. GSM performance parameters for the target microcell in an overlaid macrocell/microcell scenario

Figure 6.12 shows the performance characteristics (P_{hf}, P_{nb}) for the existing GSM services in the target microcell when N_{gprs} = 4 and different handover prioritization schemes are used, and an overlaid macrocell is considered. The values are measured for a A_{off} = 21 Erlangs in the target microcell, which implies a blocking probability of 2% (worst case situation) in the case of the GSM network operating without GPRS PS implementation yet. Values of P_{hf} and P_{nb} for the basic microcell scenario studied in the previous section (without considering the umbrella macrocell) are given for comparison purposes. From figure 6.12.(a), one can clearly see that values of P_{hf} are smaller when the overlaid macrocell is deployed, because more channels are available for fast-moving mobiles. Since the traffic for this fast-moving mobiles is carried by the macrocell, less traffic must be carried by the target microcell, so values of P_{nb} should also be smaller than in the case of no overlaid macrocell, which can be clearly seen in figure 6.12.(b). Moreover, values of P_{nb} using any handover prioritization scheme for the overlaid macrocell/microcell scenario are even smaller than that of the microcell scenario when the NPS is used (6.68%), except when the RCS-post is used.

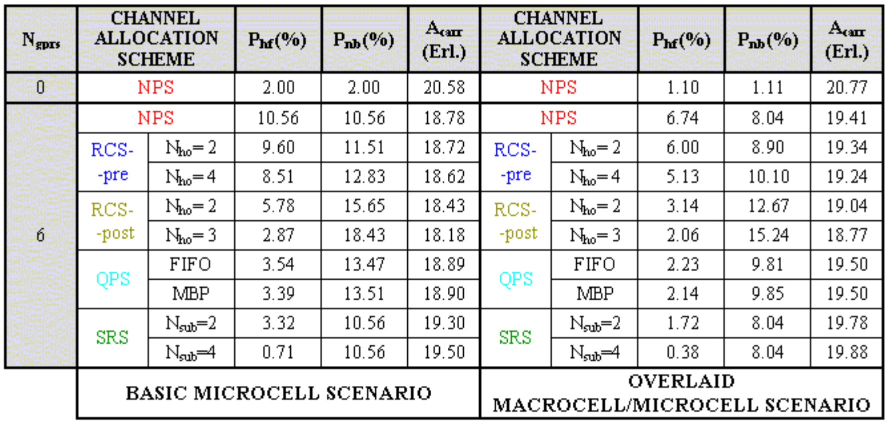
Finally, a comparison between both simulated scenarios is given in table 6.2, where all the values are referred to the target microcell and are obtained for a cell offered load of 21 Erlangs, which implies a blocking probability of 2% (worst case situation) in the case of the GSM network operating without GPRS PS implementation yet. For N_{gprs} = 2, the increase in



N_{gprs}	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)
0	NPS		2.00	2.00	20.58	NPS		1.10	1.11	20.77
4	NPS		6.68	6.68	19.59	NPS		3.99	4.73	20.06
	RCS--pre	N_{ho}= 1	6.33	6.88	19.59	RCS--pre	N_{ho}= 1	3.90	4.85	20.05
		N_{ho}= 2	6.00	7.18	19.57		N_{ho}= 2	3.60	5.12	20.04
		N_{ho}= 3	5.81	7.54	19.54		N_{ho}= 3	3.42	5.47	20.00
		N_{ho}= 4	5.48	8.10	19.49		N_{ho}= 4	3.15	5.85	19.97
	RCS--post	N_{ho}= 1	4.74	8.48	19.49	RCS--post	N_{ho}= 1	2.62	6.20	19.96
		N_{ho}= 2	3.32	10.64	19.30		N_{ho}= 2	1.72	8.02	19.78
		N_{ho}= 3	2.25	13.06	19.05		N_{ho}= 3	1.07	10.24	19.52
		N_{ho}= 4	1.53	15.61	18.75		N_{ho}= 4	0.68	12.62	19.23
	QPS	FIFO	2.11	8.44	19.69	QPS	FIFO	1.26	5.68	20.13
		MBP	1.94	8.46	19.70		MBP	1.20	5.74	20.13
	SRS	N_{sub}=1	3.47	6.68	19.83	SRS	N_{sub}=1	1.94	4.73	20.22
		N_{sub}=2	1.72	6.68	19.96		N_{sub}=2	0.88	4.73	20.29
		N_{sub}=3	0.77	6.68	20.03		N_{sub}=3	0.43	4.73	20.32
		N_{sub}=4	0.33	6.68	20.06		N_{sub}=4	0.22	4.73	20.35
	BASIC MICROCELL SCENARIO					OVERLAID MACROCELL/MICROCELL SCENARIO				



N_{gprs}	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)
0	NPS		2.00	2.00	20.58	NPS		1.10	1.11	20.77
2	NPS		3.82	3.82	20.19	NPS		2.14	2.42	20.51
	RCS--pre	N_{ho}= 2	3.58	4.11	20.17	RCS--pre	N_{ho}= 2	1.95	2.68	20.49
		N_{ho}= 4	3.17	4.58	20.14		N_{ho}= 4	1.72	3.07	20.45
	RCS--post	N_{ho}= 2	1.72	6.67	19.96	RCS--post	N_{ho}= 2	0.88	4.72	20.29
		N_{ho}= 3	1.17	8.50	19.75		N_{ho}= 3	0.54	6.20	20.11
	QPS	FIFO	1.10	4.75	20.26	QPS	FIFO	0.67	2.94	20.55
		MBP	1.08	4.82	20.26		MBP	0.65	2.96	20.55
	SRS	N_{sub}=2	0.85	3.82	20.41	SRS	N_{sub}=2	0.44	2.42	20.64
		N_{sub}=4	0.13	3.82	20.46		N_{sub}=4	0.14	2.42	20.67
	BASIC MICROCELL SCENARIO					OVERLAID MACROCELL/MICROCELL SCENARIO				



N_{gprs}	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)	CHANNEL ALLOCATION SCHEME		P_{hf}(%)	P_{nb}(%)	A_{carr} (Erl.)
0	NPS		2.00	2.00	20.58	NPS		1.10	1.11	20.77
6	NPS		10.56	10.56	18.78	NPS		6.74	8.04	19.41
	RCS--pre	N_{ho}= 2	9.60	11.51	18.72	RCS--pre	N_{ho}= 2	6.00	8.90	19.34
		N_{ho}= 4	8.51	12.83	18.62		N_{ho}= 4	5.13	10.10	19.24
	RCS--post	N_{ho}= 2	5.78	15.65	18.43	RCS--post	N_{ho}= 2	3.14	12.67	19.04
		N_{ho}= 3	2.87	18.43	18.18		N_{ho}= 3	2.06	15.24	18.77
	QPS	FIFO	3.54	13.47	18.89	QPS	FIFO	2.23	9.81	19.50
		MBP	3.39	13.51	18.90		MBP	2.14	9.85	19.50
	SRS	N_{sub}=2	3.32	10.56	19.30	SRS	N_{sub}=2	1.72	8.04	19.78
		N_{sub}=4	0.71	10.56	19.50		N_{sub}=4	0.38	8.04	19.88
	BASIC MICROCELL SCENARIO					OVERLAID MACROCELL/MICROCELL SCENARIO				

Table 6.2. Summary of performance parameters for both scenarios when A_{off}=21 Erlangs

P_{nb} is almost negligible compared to the benefit of reserving 2 additional channels for GPRS users [8], especially when the umbrella macrocell is deployed. Only the RCS-post scheme guves untolerable values of P_{nb}, which suggests that this handover scheme should not be used (unless a higher value of f_{ho} is considered). For $N_{gprs} = 4$ and 6, it can be observed that the considerable increase in P_{nb} for the basic microcell scenario, especially when the RCS-post scheme is used, seems too high price to pay for the decrease achieved in P_{hf}, and an umbrella macrocell should be considered in those cases. Furthermore, when $N_{gprs} = 6$ is needed (e.g., the GPRS penetration factor is very high), the values of either P_{hf} of P_{nb} rise unacceptable levels no matter which handover scheme is used and no matter the macrocell overlaid. Therefore, capacity is bound to increase in this case by installing a new TRX or a new site in order to keep up with the quality demands of GPRS users at the same time that ensuring the capacity of existing GSM users.

6.4.3. Commentaries on the simulation

Considering the level of complexity of the real cellular scenario to study, several assumptions were made in order to simplify the simulation. For example, a FCA was supposed, which means that values of parameters N_{gprs}, N_{ho}, N_{sub} are assumed to be fixed. However, in practice, a DCA is implemented, which allows a dynamic changing of these parameters based on traffic load supervision. Therefore, flexible adaptation to different traffic conditions is possible by changing these parameters, which means that the performance parameters that can be obtained at any time are the best possible ones. Furthermore, since data traffic tends to cause drastic peaks between low traffic periods [24], dynamic changing of these parameters allows the system to quickly respond to these peaks, so both types of traffic can be served in the best way.

Furthermore, a fixed frequency assignment was employed, which means that a set of radio frequencies are permanently assigned to the microcell (N_t is a fixed value). However, by using other frequency assignment strategies (see table 5.1) it is possible to temporarily increase the capacity in the microcell without requiring new spectrum, although new TRXs are needed, which implies more investments for the operator.

Another important matter is that all capacity calculations that were evaluated for a particular value of A_{off} to the cell, were made to simulate the worst case situation, which gives maximum values for parameters P_{hf} and P_{nb} and minimum values for A_{carr}. This worst case situation evaluates the performance parameters for the mean offered load in the rush hour.

Therefore, the actual capacity reduction experienced by GSM services would be less than that obtained in all the studied cases, because real offered traffic will be usually smaller than that considered for the worst case situation.

Finally, cells belonging to different areas, with different number of TRXs, different radius, different percentage of handover traffic, etc can be easily studied with the simulator just by changing the system model parameters properly to model the new situation as accurate as possible.

6.5. Conclusions and future work

In this Thesis a comprehensive performance study of radio resource sharing between GSM and GPRS users was performed. A literature survey on the key concepts of GPRS and the performance of the GPRS service was made. The effects of GPRS PS implementation in a GSM network on capacity of existing GSM services were computed. A simplified case study of a GPRS/GSM network was simulated considering two different scenarios; a basic microcell scenario and an overlaid macrocell/microcell scenario. The teletraffic performance of GSM services in the target microcell was measured with gradually increasing the GPRS traffic, and different handover priority-based channel allocation schemes were proposed to enhance the handover performance.

The results of the simulation were thoroughly discussed in the previous sections. Particular results for a microcell with $N_{trx} = 4$ can be summarized in the following way:

- For $N_{gprs} = 1$ and 2 (“low” GPRS penetration factor), the reduction of capacity for GSM services is almost negligible compared to the benefit of reserving additional channels to GPRS users.
- For $N_{gprs} = 4$ (“medium” GPRS penetration factor), the reduction of capacity for GSM services is considerable and handover prioritization schemes must be used. If reducing probability of handover failure is more important than increasing total carried traffic, then RCS, QPS and SRS are better than NPS; if not, an umbrella macrocell must be considered to reduce unacceptable levels of probability of new call blocking.
- For $N_{gprs} = 6$ and 8 (“high” GPRS penetration factor), the reduction of capacity for GSM services is excessive and the overlaid macrocell is not enough to ensure sufficient capacity for GSM services, so a capacity expansion is necessary.

From the results obtained in the simualtions, some general conclusions can be drawn. As a whole, it can be said that the more N_{gprs} channels are exclusively reserved for GPRS, the more the GSM capacity is degraded. Furthermore, it is observed that depending on the type of cell (cell radius, value of N_{trx}, etc) and the value of N_{gprs}, different handover prioritization schemes should be used in order to ensure a maximum handover performance. The selection of a particular handover prioritization scheme is a tradeoff between its implementation complexity and performance. If implementation cost is a major concern, then RCS and NPS should be considered. To achieve the best handover performance (with a slight voice quality degradation), SRS should be selected. The QPS would be the best choice in terms of GoS and spectrum efficiency tradeoff. Finally, in order to successfully allow a significant growth of GPRS users without heavily degrading the GSM capacity, an overlaid macrocell/microcell might be not enough and a capacity expansion would be necessary, which can be obtained by installing new TRXs in the microcell or new sites.

An interesting subject for future work would be a performance study of both GPRS and GSM services using different handover prioritization schemes. An accurate GPRS traffic model (e.g, WWW traffic model [46]) could be added to the simulator and then both systems' performance could be evaluated under different percentages of GPRS users as well as for different scenarios. This new study could give valuable hints for networks designers on which handover scheme should be used and on how many channels should be allocated for GPRS for a given amount of traffic in order to guarantee appropriate quality and capacity for both services.

Chapter 7

Guidelines for GPRS/GSM network planning

For circuit networks like GSM the challenges in network deployment have been the provision of continuous coverage and high reliability of handovers. Failure in one of these planning criteria would mean dropped calls and inadequate quality. For packet networks the situation is different: the nature of service is discontinuous, delay requirements are relieved from those of circuit switched services, and the possibility of retransmission gives an additional means to guarantee the QoS. Therefore, introduction of a packet data service like GPRS in the GSM network creates new challenges to network planning.

Traditionally, cellular network planning has been divided into four parts: capacity, coverage, frequency and parameter planning. Normally, when starting to create a network from scratch, these planning aspects follow each other logically. Introducing GPRS service to a GSM cellular network may cause changes to all of these planning aspects.

- **Capacity planning**

The purpose of capacity planning is to make the network capacity match the offered traffic created by users. The capacity need can be estimated with the help of several factors, as the traffic density generated (depending on the environment characteristic), the mix of terminal types, the demographic situation, the penetration factor of every service, the popularity of applications, the desired QoS/GoS level, etc. According to these factors, the distribution of the traffic demand for both the GSM and the GPRS service can be estimated.

For GSM services, the capacity can be estimated well enough by using the Erlang-B formula when no handover priority is considered (see equation (1)). If any handover prioritization scheme is applied, then the analytical models developed for every scheme can be used, although in practice the actual values might vary compared to the pure theoretical approach. The Erlang-B formula cannot be used directly for GPRS capacity planning due to the bursty characteristics of GPRS traffic. Several packet-data-oriented traffic models have been developed based on measurements from actual data networks [27], but their applicability to radio network modeling is still to be proven.

GPRS is supposed to utilize those resources which are not used by the GSM services. One way to explore the usable bandwidth for the GPRS traffic is to calculate the average GSM traffic capacity used in the network; ideally the rest of the resources are, on average, available for GPRS connections (see figure 6.3). This is not exactly correct because reserving and releasing the packet data connections takes a bit of time, but this should provide an approximation about the nature of the resources. The operator can also decide to dedicate permanently some physical channels for GPRS traffic. For such a dynamically variable resource and the bursty traffic, the capacity offered by the network may only be obtained from simulations. Furthermore, in order not to damage the quality of existing GSM services, the remaining capacity of the network should be correctly evaluated considering interference constraints; the maximum radio resources enabled to be allocated to GPRS are defined by this network remaining capacity and are dependent on the outage or interference level of the existing network [28]. Therefore, admission control of GPRS is needed before allocating the channels to GPRS in order to guarantee the QoS of existing GSM users.

In conclusion, the resources which can be allocated to GPRS and the radio resource allocation technique to be used (CS or PS) depend on the outage level of the existing network, the blocking probability target for existing GSM services and the number of TRXs available in the BTS. Therefore, it can be concluded that capacity planning in an overlaid GPRS/GSM network is a tradeoff process between the quality and capacity of existing GSM services and the capacity gain of GPRS. After the maximum number of channels allocated to GPRS and the channel allocation technique are decided from the last planning procedure, the next step is to simulate the system performance in order to obtain the performance parameters (in practical GPRS planning it should be done by computer automatically).

- **Coverage planning**

The main purpose of coverage planning is to provide the required radio coverage with specified time and location probability. The process of coverage planning has several initial conditions: the preliminary capacity plan, the service area topology, the propagation models, the system and equipment specification as well as the desired QoS, all affect the coverage plan. In traditional GSM services, the goal of making a coverage prediction can be achieved by calculating the link budget (using radio wave propagation formulas), which depends on used power levels, antenna gains, receiver sensitivities, etc. This link budget must be calculated for both uplink and downlink in order to guarantee about the same QoS in both directions.

Since GPRS is deployed on top of an existing GSM network, the same link budget as that of GSM services may be used for GPRS. However, it is necessary to consider that the outage probability near to the cell border area will increase as more channels are used for GPRS. Then, if the degradation of service coverage occurs temporarily, it will not be a problem for GPRS because the transmission can be delayed and retransmitted. But if the effect is in long term it will be necessary to face the network reconfiguration problem, e.g., installing new TRXs or new BTSs, or having a larger reuse factor and more frequency carriers. Another aspect that should be taken into account is the effect of network load: the more timeslots in use at the same time, the higher the interference level will be [28]. Compared to the normal GSM traffic busy hour with certain blocking probability, the addition of GPRS will have an impact on both the overall GSM quality and capacity and its own quality, if no new resources are allocated for GPRS (e.g., increasing the number of TRXs).

- **Frequency planning**

The frequency planning utilizes the results gained from the capacity and coverage planning and its objective is to find out the most effective way to use the radio resources available for the operator's use. For GSM services, the main task of the frequency planning is to determine the optimal reuse factor. The most important factors that limit frequency use in GSM are the available bandwidth in use and the signal-to-interference ratio (SIR) requirement, which is defined by system specifications. GPRS does not require compulsory permanently allocated PDCHs; the operator can decide to dedicate permanently or temporarily some physical channels for GPRS traffic. If some channels are exclusively dedicated to GPRS, a small change in the original frequency planning might be needed in order to meet the new capacity demand and the new SIR requirement for GPRS. Furthermore, if the popularity of the GPRS service becomes very high, the installation of new TRXs in the existing cell sites might be needed, or even new cell sites. These additional TRXs require frequencies and assuming that no new bandwidth is given to the operator's use, the frequency space should be re-planned.

- **Parameter planning**

The parameter planning enables network tuning once the hardware is determined. The importance of careful parameter planning is very high, because it allows the network to adjust flexibly to fast changes of traffic type and load that may occur. GPRS service will introduce several new parameters, such as cell selection and reselection criteria, power control, routing area, and new packet-specific channel definitions. These new parameters are software release dependent, so manufacturers may have different solutions as well. The final effects of parameter fine-tuning will be seen after the live network measurements.

The planning task becomes even more challenging when the HSCSD service [6] is introduced to the same network. Since the circuit switched traffic is prioritized over GPRS in the shared band, the possibility of HSCSD traffic blocking GPRS traffic must be considered when the GPRS CS implementation takes place or PS implementation with small N_{gprs}. To avoid this, a maximum HSCSD capacity allowed in the system could be set; then, HSCSD would still be prioritized, but at least some channels would be always left for GPRS use as well.

Finally, radio network planning is a field where even the most complicated models rarely match perfectly to the real behavior of the network. Guidelines exist and offer indispensable assistance, but they are only helpful tools and the tuning is often completed based on field testing in order to attain the network quality desired.

APPENDIX 1

The handover mechanism

Handover is the mechanism that transfers an ongoing call from one cell to another as a user moves through the coverage area of a cellular system. In order to detect the need for handover, the MS needs to take power measurements on the channel it is currently using as well as the broadcast channels of the neighboring cells. The handover process is initiated when the power received by the MS from the BTS of a neighboring cell (target BTS) exceeds the power received from the current BTS by a certain amount. This is a fixed value called the *handover threshold* (also called *hysteresis margin*). For successful handover, a channel must be granted to the handover request before the power received by the MS from the current BTS reaches the *receiver threshold*. The receiver threshold is the point at which the received power from the current BTS is at the minimum acceptable level. At this point, since communicating with the current BTS is no longer possible, the call will be terminated unless a successful handover to an eligible cell has already occurred. A sophisticated averaging process for the power measurements is assumed, so fast fading is eliminated in the measurement process [3]. The *handover area* is the area where the ratio of received power levels from the current and the target BTS is between the handover and receiver thresholds, that is, the overlapping area between adjacent cell coverages. The time that a MS moves across the handover area is referred as the degradation interval.

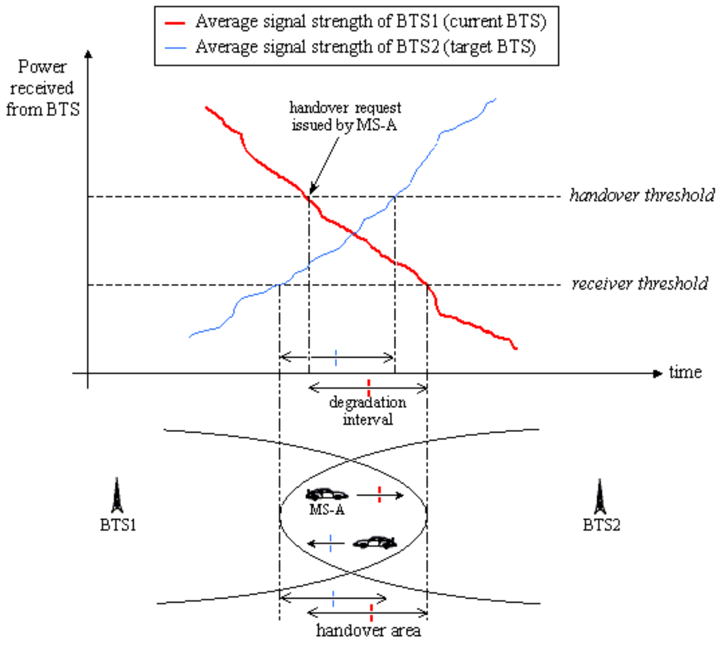


Figure A.1. The handover process

APPENDIX 2

Class Hierarchy of the Simulation Library

	Class	Description
Root	SMObject	Root of the simulaiton class hierarchy: object management and error handling
Random numbers	SMRandomGenerationBase	Abstract base class for random number generators
	SMRandom GeneratorLCG	Linear congruence random number generator
	SMRandomGeneratorMLCG	Multiple linear congruence random number generator
	SMRandomDistributionBase	Abstract base class for random number distributions
	SMRandomDistributionNegExp	Negative exponential distribution
	SMRandomDistributionPoisson	Poisson distribution
	SMRandomDistributionUniform	Uniform distribution
	SMRandomDistributionNormal	Normal distribution
	SMRandomDistributionRice	Rice distribution
	SMRandomDistributionRayleigh	Rayleigh distribution
Statistical evaluation	SMDataCollectionBase	Abstract base class for statistical evaluation
	SMDataStatistics	Evaluation of statistics of an input sequence
	SMDataHistogram	Reduction of statistical data to a simple histogram
	SMDataFileToPlot	Data storage for ploting in MATLAB
Container classes	SMSingleLinkedList	Single linked list of objects
	SMSLListNode	Node of single linked list
	SMSLListIterator	Iterator of single linked list
	SMDoublyLinkedList	Doubly linked list of objects
	SMDLListNode	Node of doubly linked list
	SMDLListIterator	Iterator of doubly linked list
	SMQueueBase	Abstract base class for queueing of objects
	SMQueueFIFO	FIFO queue
	SMQueueSPT	SPT queue (objects ordered by shortest processing time)
Event-driven simulation	SMDLListNode	Node of doubly linked list
	SMEvent	Generic data type for events used in the simulation
	SMEventList	List of events
	SMEventHandler	Abstract base class for creating simulation event handlers
	SMEventSchedulerBase	Abstract base class for event schedulers
	SMEventScheduler	Central simualtion tool
	SMEventIteratorBase	Abstract base class for event iterators
	SMEventListIterator	Iterator for an event list
Simulation tools	SMSimTime	Current simualtion time
	SMJob	Standard job object for the queues
	SMArray1Base	Abstract base class for 1-dimensional arrays
	SMArray1Int	1-dimensional array for integers
	SMArray1Double	1-dimensional array for doubles
	SMArray2Base	Abstract base class for 2-dimensional arrays
	SMArray2Int	2-dimensional array for integers
	SMArray2Double	2-dimensional array for doubles

APPENDIX 3

Example of performance parameters obtained in a simulation run

```
NEW SIMULATION:   | Nn = 400000 |
*******************************************************************************************
 PARAMETERS:
  Carriers (TRXs) = 4  Channels = 32 { SIG=3 , GPRS=4 , HO=1 , SUB=0 }
  Total offered traffic = 21 Erlangs
   Percentage of voice traffic       = 65%
   Percentage of handover traffic = 35%

 TRAFFIC MODELS:
   Mean velocity of the mobiles  = 30 km/h   ,   std deviation of the velocity   = 20 km/h

   Voice Traffic:                                              Handover traffic:
      Voice traffic generated = 13.65 Erlangs                     Handover traffic generated = 7.35 Erlangs
      Potential users that can be served = 682 users              Potential users that can be served = 367 users
      Mean interarrival time = 4.3956 seconds                     Mean interarrival time = 8.16327 seconds
      Mean service time = 60 seconds                              Mean service time = 60 seconds

 HANDOVER PRIORITIZATION SCHEME: (hybrid scheme)
 .RCS: channels exclusively for handovers = 1
 .QPS-FIFO: maximum length of the queue = 10
    Degradation interval: normal distribution with  mean  = 6 seconds and std deviation = 4 seconds

 REAL TIME SIMULATED:
  Simulation time in seconds = 1.75429e+006 seconds (20 d 7 h 18 m 13 s)

 SIMULATION RESULTS:

  Number of new calls generated (Nn)             = 400000
  Number of incoming handover requests (Nh) = 215067
  Number of blocked calls (Nnb)                    = 34180
  Number of handover failures (Nhf)              = 4304

  Average delay in serving handovers in queue = 2.17584 seconds

  Total Channel Utilization    : 78.8559%

  [        SG |  88.37% |  95.39% |  94.86% |  94.39% |  93.81% |    93.2% |  92.44% ]
  [        SG |  91.77% |  90.89% |  89.76% |  88.62% |  87.12% |  85.63% |  83.64% ]
  [        SG |  81.73% |  79.17% |    76.4% |  73.34% |  69.58% |  65.92% |  61.46% ]
  [       DA |        DA |        DA |        DA |  56.36% |  51.55% |  45.96% |  40.02% ]

  Voice Channel Utilization    : 52.16%

  [        SG |       HO  |  64.27% |   63.4% |   63.21% |  63.29% |  62.62%|  62.75% ]
  [        SG |  61.53% |  60.64% |  60.44% |  59.48% |  58.12% |    57.3% |  55.87% ]
  [        SG |  53.78% |  51.51% |  50.99% |  47.67% |  45.97% |  42.93% |  39.84% ]
  [       DA |        DA |        DA |        DA |    36.7% |  33.61% |  29.61% |  26.19% ]

  Handover Channel Utilization : 28.79%

  [        SG |  88.37% |  31.12% |  31.46% |  31.18% |  30.52% |  30.58% |    29.7% ]
  [        SG |  30.24% |  30.25% |  29.32% |  29.14% |       29% |  28.33% |  27.77% ]
  [        SG |  27.95% |  27.66% |  25.41% |  25.67% |  23.61% |  22.99% |  21.63% ]
  [       DA |        DA |        DA |        DA |  19.66% |  17.94% |  16.34% |  13.83% ]

  Handover Reserved Band Utilization (Nho)   : 88.37%
  Total Shared Band Utilization (Nshared)       : 78.46%
  Handover Shared Band Utilization (Nshared) : 26.3%

  Handover Failure Probability  = 2.00124%
  New Call Blocking Probability = 8.545%
  Offered traffic = 21 Erlangs
  Carried traffic = 19.6865 Erlangs
  Ratio of carried vs. offered traffic = 93.7453%
  Cell Utilization = 78.8559%

  Time needed to execute the simulation: 334 seconds
*******************************************************************************************
```

APPENDIX 4

Flow charts of the simulation program

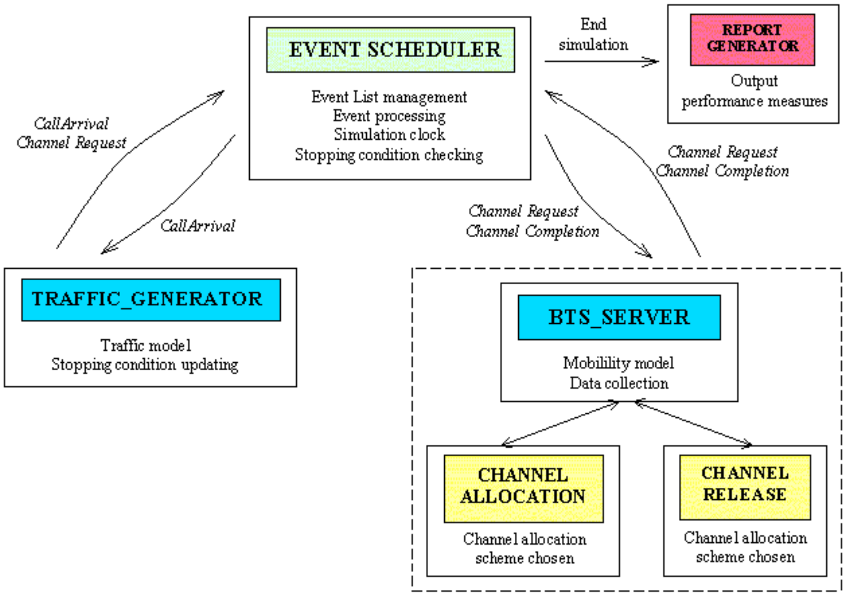
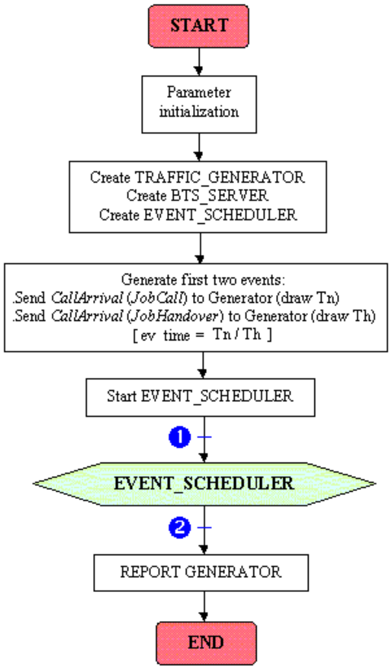


Figure A.2. Structural elements of the simulation model



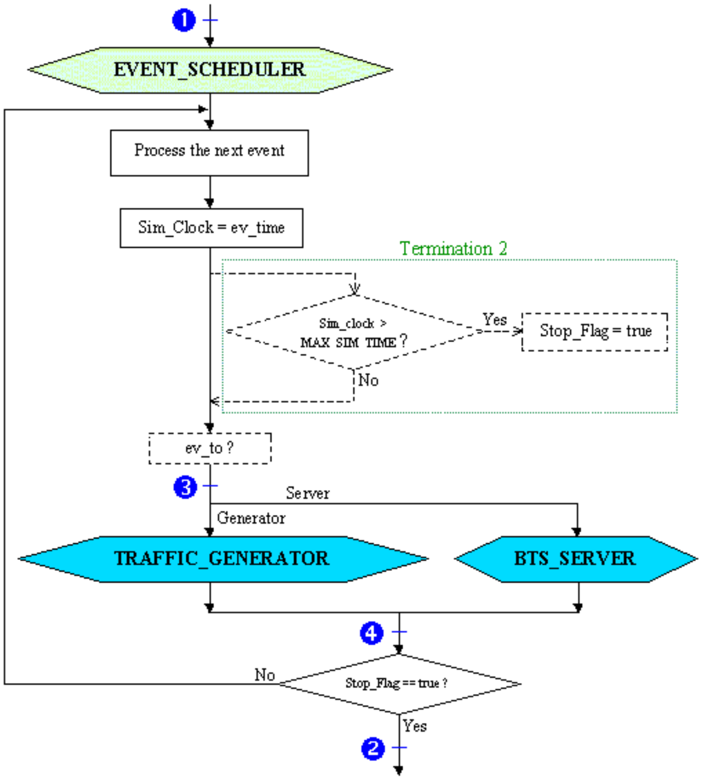


Figure A.3. Main program **Figure A.4. Event Scheduler**

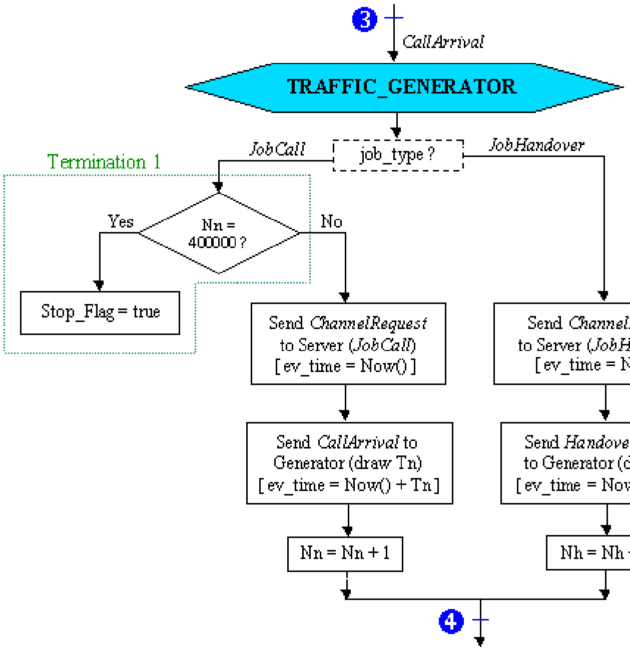


Figure A.5. Traffic_Generator

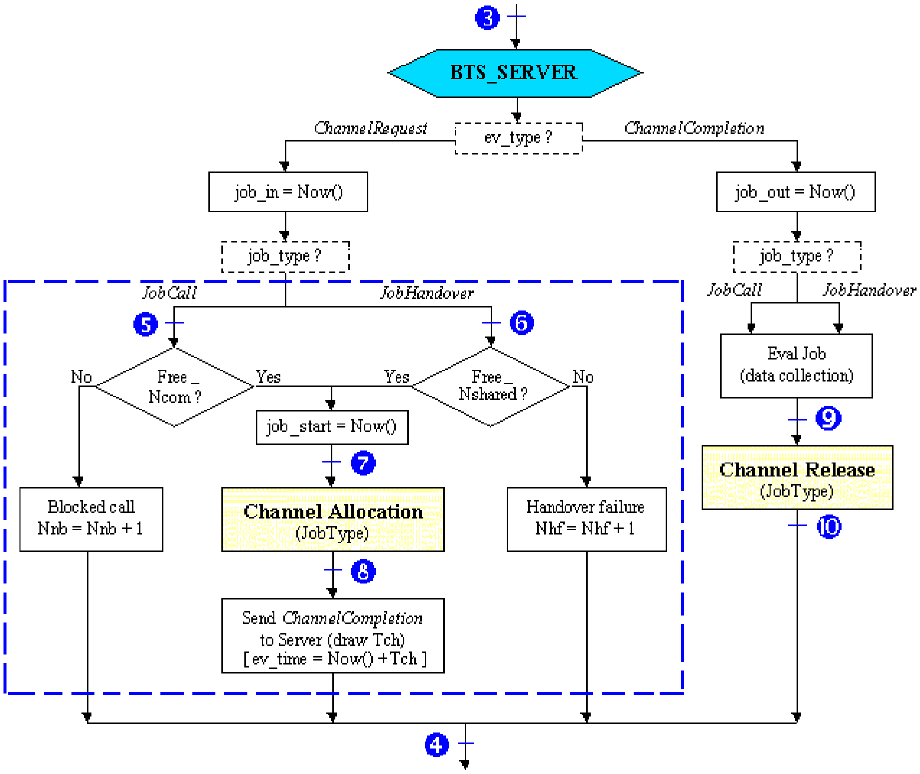


Figure A.6.a. BTS_Server (NPS and RCS)

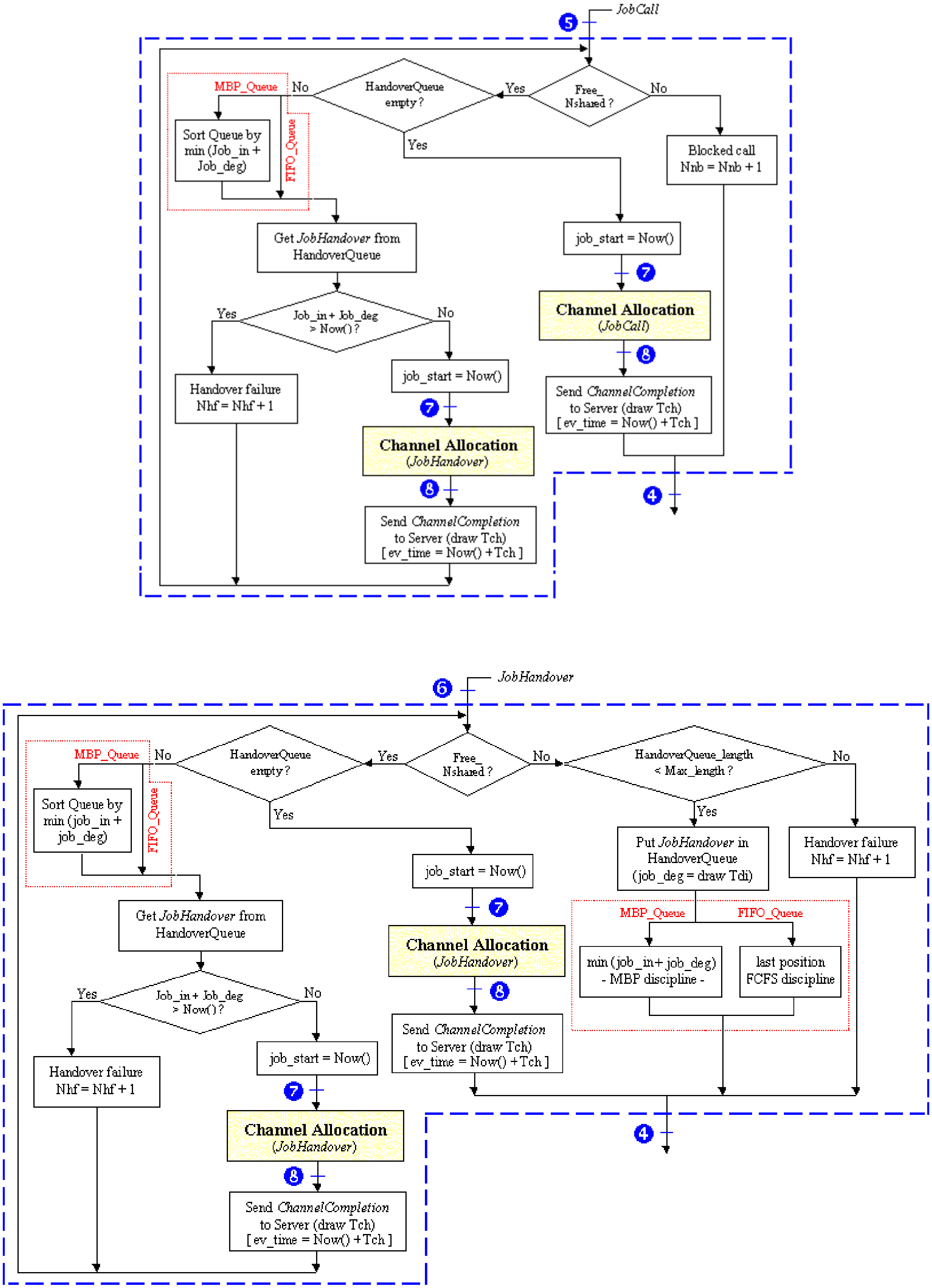


Figure A.6.b. BTS_Server (QPS)

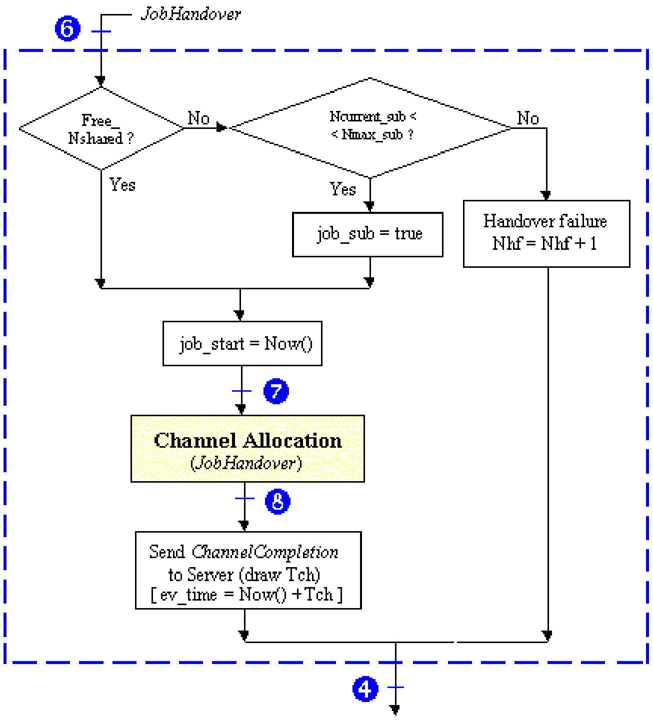
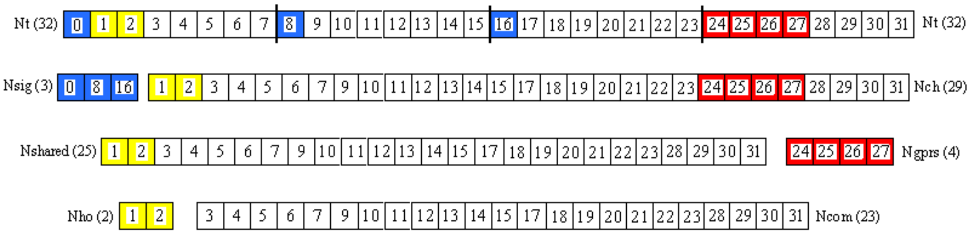


Figure A.6.c. BTS_Server (SRS)


Nt (32) 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 Nt (32)

Nsig (3) 0 8 16 — 1 2 3 4 5 6 7 9 10 11 12 13 14 15 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 Nch (29)

Nshared (25) 1 2 3 4 5 6 7 9 10 11 12 13 14 15 17 18 19 20 21 22 23 28 29 30 31 — 24 25 26 27 Ngprs (4)

Nho (2) 1 2 — 3 4 5 6 7 9 10 11 12 13 14 15 17 18 19 20 21 22 23 28 29 30 31 Ncom (23)

Figure A.7. Example of channel allocation for a BTS with $N_{trx} = 4$

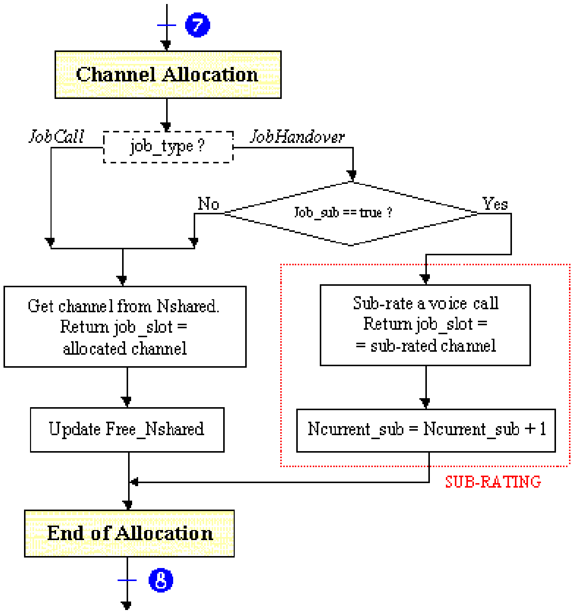
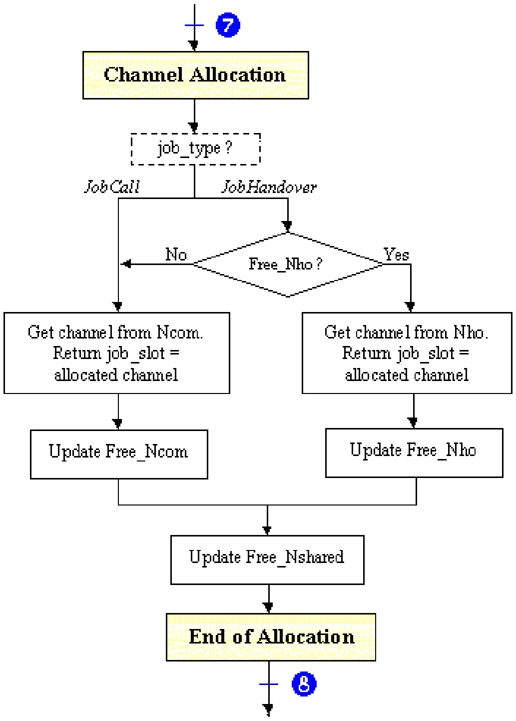


Figure A.8.a. Channel Allocation (NPS,QPS and SRS)



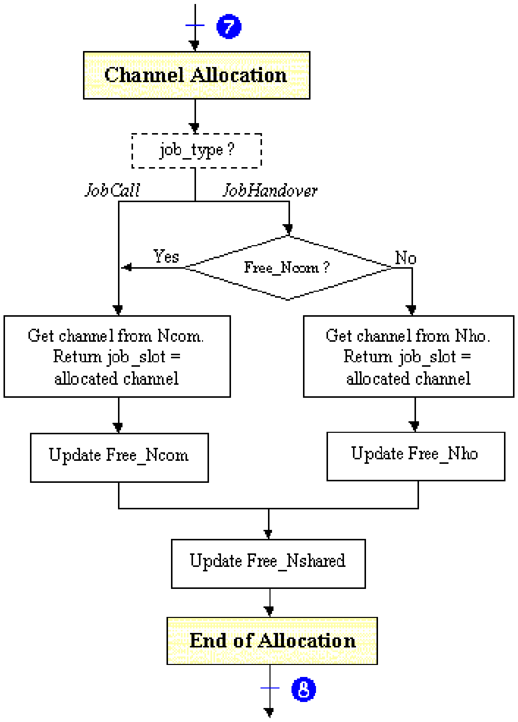
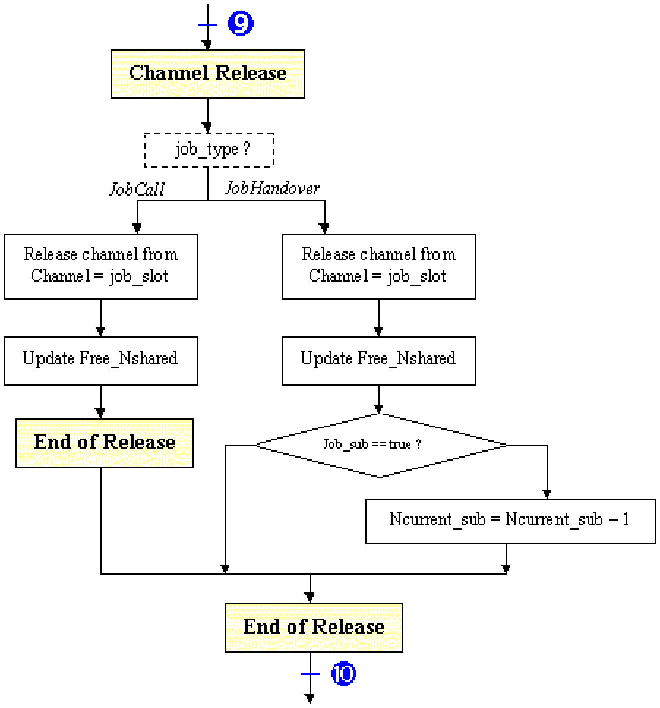


Figure A.8.b. Channel Allocation (RCS-pre)

Figure A.8.c. Channel Allocation (RCS-post)



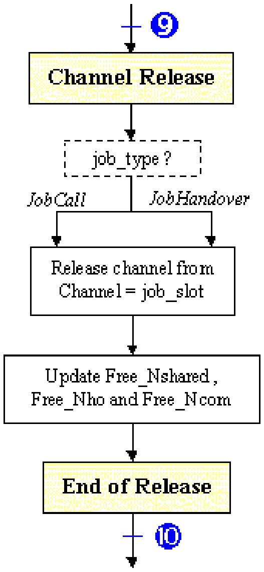


Figure A.9.a. Channel Release (NPS,QPS and SRS)

Figure A.9.b. Channel Release (RCS)

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