Department of Communication Networks

Aachen Technical University (RWTH)

Prof. Dr.-Ing. B. Walke

Diploma Paper

Simulative and analytical study of measures supporting the quality of service in a radio-based ATM network

by

Ulrich Vornefeld

Student ID No. 187020

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Mentors:
Prof. Dr.-Ing. B. Walke, Associate Professor
Dipl.-Ing. D. Petras
Dipl.-Ing. A. Hettich

I hereby confirm that I have conducted this work independently without the assistance from third parties – except for the official mentoring by the department. All literature used for this paper is listed completely in the Bibliography section.

Aachen, April 1, 1997

(Ulrich Vornefeld)

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CHAPTER 1

Introduction

Increasing globalization and internationalization of society and the demand for information that goes with it constantly increase the information provision and information transmission requirements that communication networks have to meet. The development of these networks is essentially driven by two trends: by integration of the various telecommunications services within one network and by accounting for demands for individual mobility and universal accessibility. These trends have resulted in the development and introduction of narrowband ISDN (*Integrated Services Digital Network*) and digital mobile telephone networks based on the GSM standard (*Global System for Mobile Communication*). ISDN eliminates the large number of different network user interfaces and assigns voice, text, and data services via a uniform interface.

The introduction of new interactive and real-time oriented services and the constantly growing need for bandwidth of the Internet ensure continuous development of the worldwide cable-based infrastructure towards multimedia broadband ISDN, which is popularly called the "information highway." This network utilizes more and more of a new transmission and switching technology called ATM (*Asynchronous Transfer Mode*) [6, 9, 29]. It is expected that the trend towards universal accessibility in conjunction with wireless access to multimedia services will be one of the major drivers of telecommunications in the near future [18].

Progress made in recent years in microelectronics and signal processing has made the implementation of wireless terminals for B-ISDN based on ATM technology a realistic possibility. The industry and the universities are responding with increased research activities in the field of wireless ATM networks (for an overview, see the Introduction of [16]). Wireless ATM workgroups (WAG) were formed at the European Telecommunications Standards Institute (ETSI) and the ATM Forum, who study the requirements and architectures of W-ATM systems [26, 4]. It is planned to adopt first technical standards by the end of 1998. The technological conditions for wireless communications systems with transmission rates of several 10 Mbit/s per connection were created by releasing the respective frequency range for personal communications systems in the 5 GHz range.

This paper interprets the radio interface as a distributed ATM multiplexer that performs statistical multiplexing of ATM cells on the radio channel. An operating strategy with static and dynamic priorities is used to determine the transmission sequence of ATM cells. The system and protocol aspects of the W-ATM radio interface that determine the transmission sequence of the ATM cells and perform the multiplexing functions are examined in order to meet the quality of service requirements of all ATM service classes through suitable extensions, algorithms, and modifications. These extensions, algorithms, and modifications are called measures supporting the quality of service in this paper.

Overview of the paper

After a brief introduction to ATM technology in Chapter 2, Chapter 3 presents the architecture of the ATM radio interface. The protocol stack derived from it is described in Chapter 4, with a focus on controlling the transmission sequence of the ATM cells. Chapter 5 explains the link access protocols at the radio interface, Chapter 6 details the acknowledge strategies and measures supporting the quality of service that result from these protocols. Chapter 7 provides an overview of the various aspects of the simulation model used and implemented. Chapter 8 (Performance evaluation) presents the results of the simulation.

CHAPTER 2

Asynchronous Transfer Mode, ATM

ATM stands for *asynchronous transfer mode* and denotes a new asynchronous transmission, switching, and multiplexing method that was developed to meet the continually increasing requirements posed by new services and more and more powerful computers in future broadband telecommunications networks in accordance with the I.300 series of ITU[1] Recommendations.

In ATM networks, the data streams to be transmitted are divided into fixed-length packets (cells) and transmitted asynchronously. This means that the cells of a data stream do not have fixed time slots. The cells from different connections are transmitted via a physical channel in a time-interleaved manner in the order of their arrival. The cells of one connection may not pass one another (virtual connection concept). The ATM multiplexer inserts "idle cells" into the joint output data stream if none of the connections needs transmission capacity (Figure 2.1). In this way, the physical channel may provide just as much capacity for a connection as this connection actually needs at any given point in time. In particular, this allows a response to the dynamic communication behavior of connections with changing bandwidth requirements over time (see Table 2.1). This method called *statistical multiplexing* utilizes the statistical properties of data traffic to transmit larger amounts of data than synchronous methods over a physical channel with the same capacity.

Transmission via ATM networks is based on virtual channel connections (VCCs). When the connection is set up, the ATM network determines a route via switches between the communicating terminals that is stored in the internal routing tables of these switches. All cells of the associated virtual connection are transmitted via the virtual channel formed in this way. The cells are transmitted based on the routing parameters contained in their headers which are used as pointers to the respective entries in the routing tables of the nodes.

[1] International Telecommunication Union

Service	Bit rate	Burstiness*	Delay**
Voice, telephony	64 kbit/s	1	25 ms
Video conference (low quality)	128 kbit/s	1	50-250 ms
Video conference (high quality)	1-10 Mbit/s	5	50-250 ms
Data transmission	0.1 – 30 Mbit/s	2 - 200	-

* Maximum to minimum bit rate ratio
** Max. tolerable end-to-end delay
*** without echo compensation

Table 2.1: Characteristics of some typical services [6, 17]

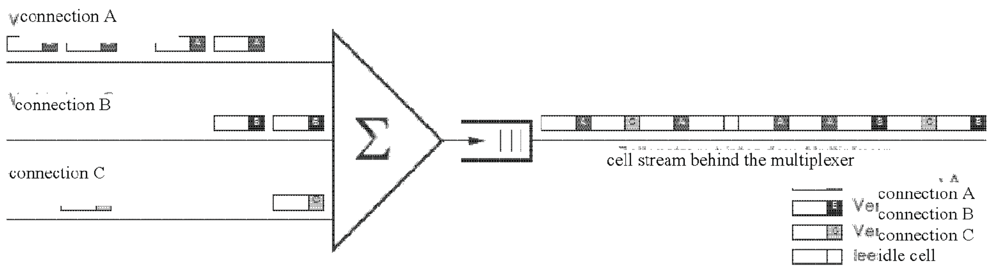


Figure 2.1: Time multiplex in the ATM method

2.1 Structure of the ATM cell and meaning of the control information

The header structure depends on whether the cells are transmitted within the network (between ATM switches) or between the network and the user or terminal (see Fig. 2.2). Two interfaces are distinguished:

- User network interface (UNI)
- Inter network interface (INI)

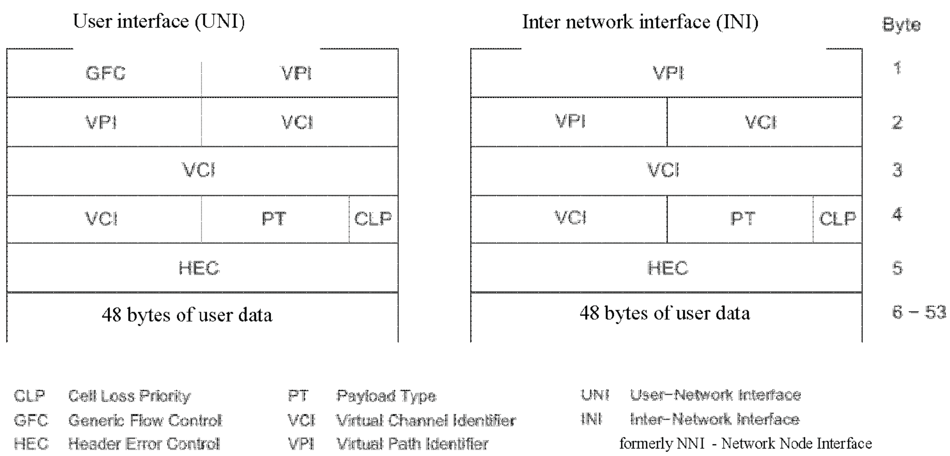


Figure 2.2: Structure of ATM cells at the UNI and INI interfaces

GFC *Generic Flow Control*, 4 bits (UNI only)

This field is used for access control of terminals at the UNI.

VCI *Virtual Channel Identifier*, 2 bytes

The reference to the virtual channel is used to distinguish among different simultaneous connections and for assigning cells to connections. The VCI is assigned to one connection section only.

VPI *Virtual Path Identifier*, 8 or 12 bits

Identifier for virtual paths identify a channel bundle, allowing to distinguish between routes going in the same direction that each contain multiple virtual channels. Switches will be able to identify and forward channels of the same bundle faster.

PT *Payload Type*, 4 bits

This field identifies the type of information field for distinguishing payload and signaling information. The latter is used for operations and maintenance (OAM) or for resource management (RM). A switch has to analyze both the header and the user data field in the body of the cell.

CLP *Cell Loss Priority*, 1 bit

This bit is used to identify low-priority cells that are preferably discarded in the event of an overload condition in the network.

HEC *Header Error Control*, 1 byte

Unlike the user data, the header of an ATM cell is protected by a check sequence. This sequence recognizes two-bit errors and corrects one-bit errors and is recalculated in each network node. In addition, HEC is used for identifying the beginning of a cell. Higher-order protocol layers are responsible for error control of user information.

2.2 ATM switching

ATM switching is based on virtual connections. The cells contain a virtual channel identifier (VCI) and a virtual path identifier (VPI) that a switching node uses to determine the next node and enters it in the header of the cell. Each switching node only knows the respective next node. The complete origin and destination addresses are sent once during connection setup to establish these virtual connections, i.e. the routing tables in the network nodes. When a cell arrives in a network node, the information in the header of the cell (VCI and VPI) is analyzed and the next network node is determined using the routing table. This results in new values for the VPI and, depending on the switching element, for the VCI as well, and this new information is entered into the cell header. Then the cell is routed to the respective output of the switching network.

Splitting the channel number into VPI and VCI requires two types of network nodes. An ATM cross connect switches the channel bundle into the respective directions based on the VPI field. The VCI field remains unchanged. An ATM switch makes virtual connections, and the VPI and VCI are analyzed and changed in the cross connect process, see Fig. 2.3.

2.3 The ATM reference model

Based on the ISO/OSI reference model, a four-layer reference model has been defined for ATM (see Fig. 2.4). These include the physical layer, the ATM layer, the ATM adaptation layer (AAL), and a layer that represents the functions of higher-order layers.

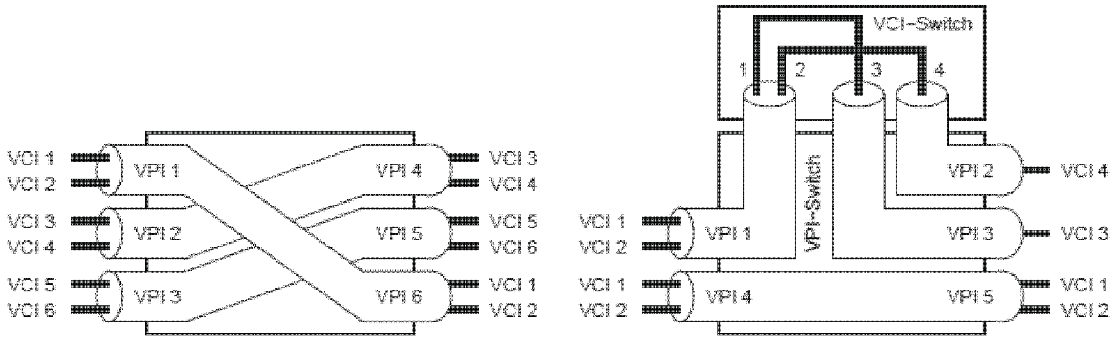
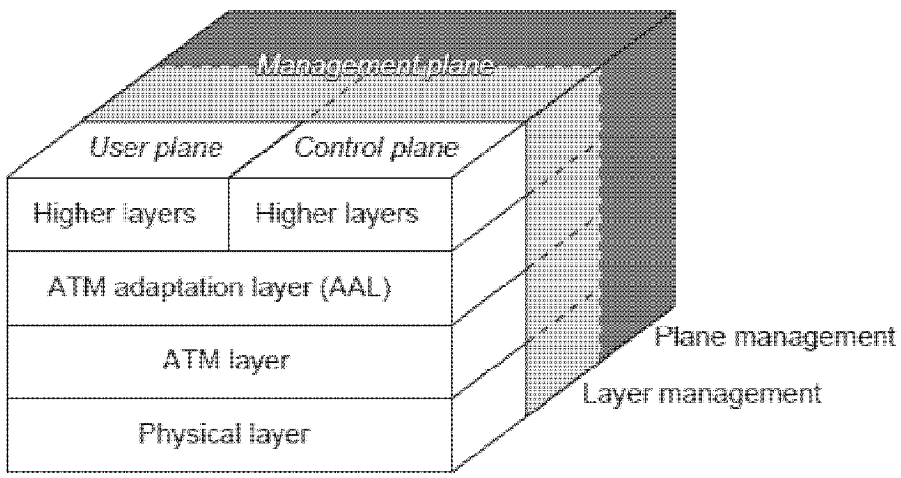


Figure 2.3: Switching through channel bundles (virtual paths) and connections in ATM-switching fields and ATM- exchanges

Three different protocol planes (planes) have been implemented: the user plane, the control plane and the management plane. The management plan includes two functions: the plane management dealing with the entire system and the management of the individual layers (layer management).



Figurer 2.4: ATM Reference model

Physical layer: The physical layer is in regards to the standard ISO/OSI layer 1-functions like bit synchronization, line code and monitoring functions. Their functionality is determined by the method of transfer.

ATM-layer: The ATM-layer corresponds with the ISO/OSI-layer 3. It contains the ATM-specific functions for cell transport:

- Control of the VPI and VCI oriented functions for the differentiation between different connections in the ATM exchange
- Multiplexes and demultiplexes of the cells from different connections
- Creation and extraction of information in the cell head
- Priority control in order to minimize cell loss and waiting times
- Functions to avoid buffer overflows (congestion control)
- Connection-specific monitoring of the cell rate in accordance with the service level agreements with the participants (usage parameter control, UPC)

- G
  eneric flow control (GFC) to the UNI

ATM-adaptation layer: The adaptation layer (AAL) affects the service-specific requirements and corresponds with the ISO/OSI layer 4. It provides services, which they provide with the help of the ATM-layer by executing the required segmentation of data streams (segmentation and reassembly sublayer, SAR) and balances delay deviations that occur with synchronous services by the ATM-network or allows for the recognition of cell losses by data services (convergence sublayer, CS). The following AAL-types were defined:

Type	Description
AAL 1	allows for synchronous transfer with constant data rates by balancing out delay deviations in the receiver
AAL 2	allows for synchronous transfer with variable data rates by balancing out delay deviations in the receiver
AAL 3/4	for data services and other non-real-time oriented services; allows for the recognition of cell and package losses; type 3 is connection-oriented, type 4 allows for unconnected transfers
S-AAL	reduced type 3 for signalizing traffic

Table 2.2: Types of the ATM-adaption layer

2.4 Service levels in the ATM-fixed network

The service levels in ATM-networks describe the connection quality, which the participant determines during the establishment of connection with the network provider in a so-called service level agreement and which must then be guaranteed by the network.

The ATM-network must be able to fulfill the requirements of different services for the service levels (quality of service, QoS) of the ATM-layer. The ITU-T recommendation E.800 defines the service levels as such:

"Collective effect of service performance which determine the degree of satisfaction of a user of service"

In this work, however, the implied subjective impressions of the service user should not be further considered in the definition above. The service levels should instead be described with the help of *network performance parameters*, which are measurable and objectively comparable to the user interfaces. The service level requirements of a connection are described with the help of this network parameters, which are defined in (12) and (3):

CER *Cell Error Ratio*:
Quotient from incorrectly transferred cells and all transferred cells

CLR. *Cell Loss Ratio*:
Quotient from lost cells and all transferred cells

CMR. *Cell Misinsertion Rate*:
Share of cells, which were transferred to the incorrect recipients

CTD *mean Cell Transfer Delay*;
Arithmetic method for the end-to-end-cell transfer duration

maxCTD *maximum Cell Transfer Delay*:
Cells whose transfer delay exceeds maxCTD are evaluated as lost

CDV *Cell Delay Variation*:
Deviation of the end-to-end-cell transfer duration

In order to be able to satisfy the traffic characteristics from different sources, four service classes were defined on the ATM-layer, which are different in their requirements for service levels, see also table 2.3:

CBR. *Constant Bit Rate*
The sources of these service classes transmit with a constant bit rate, which corresponds with the maximum bit rate, which was negotiated at the time of the connection establishment. The source has real-time requirements for the network and requires compliance of an upper limit for the maximum delay of their cells through the network. (For example: speech transmission)

VBR. *Variable Bit Rate*
VBR-sources transmit with variable bit rate. A difference is made between real-time oriented (real-time, RT) services with a defined maximum cell delay and less critical (non real-time, nRT) services). (example: video transmission)

ANR. *Available Bit Rate*
In this service class, the traffic sources adapt their bit rate dynamically to the available open resources. No requirements are placed on the real-time behavior and delay. Only the cell loss probability is defined as a parameter for the service level. (Example: data transmission)

UBR. *Unspecified bit Rate*
This service class does not offer any traffic-related service guarantees. Neither the cell loss probability nor a limit for the maximum delay are guaranteed (*Best Effort)*.

Parameter	ATM Service Class				
	CBR	VBR(RT)	VBR(NRT)	ABR	UBR
CLR	Defined	Defined	Defined	Defined	Undefined
CTD	Defined	Defined	Defined	Undefined	Undefined
maxCTD	Defined	Defined	Defined	Undefined	Undefined
CDV	Defined	Defined	Undefined	Undefined	Undefined

Table 2.3: ATM Service Classes and their Service Level Parameters

The monitoring and control of the service levels requires functions in end devices, access and switching nodes, which are summarized under the general topic of *Traffic Management* (3).

The connection admission control (CAC) checks before the admission of a desired connection to see if the authorization of another connection is possible without hindering the existing connections (14, 32). The CAC can only work correctly if the traffic of a connection does not exceed the parameters agreed upon in the service level contract. Thus, a monitoring of the connection parameters occurs on the edge of the network in order to take immediate countermeasures in the case of an exceeding the thresholds, i.e. through the discarding of all cells, which are contributing to exceeding the parameters (Usage Parameter Control (UPC), policing function).

In ATM-multiplexes and ATM-exchanges, ATM-cells with different connections compete with each other for the capacity of the outgoing multiplex lines. The processing of the cells waiting in the buffers occurs through a control unit, called a scheduler, which is based on an ideal operating strategy. The task of the scheduler is to allocate the transfer capacity of the multiplex lines corresponding with the requirements from the different connections.

CHAPTER 3

Architecture of the ATM Wireless Interface

In this chapter, initially the architecture of the ATM-wireless interface between the wireless or mobile ATM-terminal (wireless terminal, WT) and the ATM-fixed network is introduced; after this, the structure of the protocol plane will be explained and the areas will be characterized in which the measures being investigated in this work to support the service levels are used.

Image 3.1 schematically shows the structure of the basic mobile wireless network (23, 24, 26). The access points to the ATM-fixed network form base stations, which are established from one or multiple transceivers and a base station controller (BSC), which connects the base stations with the ATM-fixed network and executes the protocols of the base station.

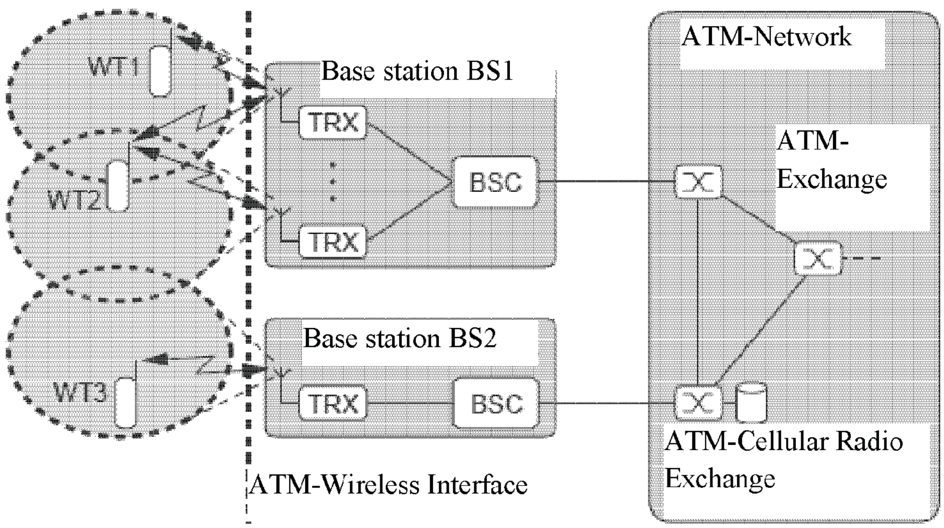


Figure 3.1: Architecture of a cellular ATM-cellular radio network

Such a function allows for wireless ATM-access in select areas, i.e. in buildings, in open areas or near buildings. Handover functions allow for the free mobility of the terminals within their areas of supply. Due to the architecture of this wireless network, there are two types of handovers, see figure 3.2:

Wireless handover: The wireless handover occurs between two transceivers from the same base station. The switching of virtual connections is executed within the base station controller and is independent of the ATM-fixed network.

Network handover: The network handover occurs between two transceivers from different base stations and requires the rerouting of virtual connections within the ATM-network. A special ATM-mobile radio exchange is required for this corresponding with the mobility functions.

Wireless handover **Network handover**

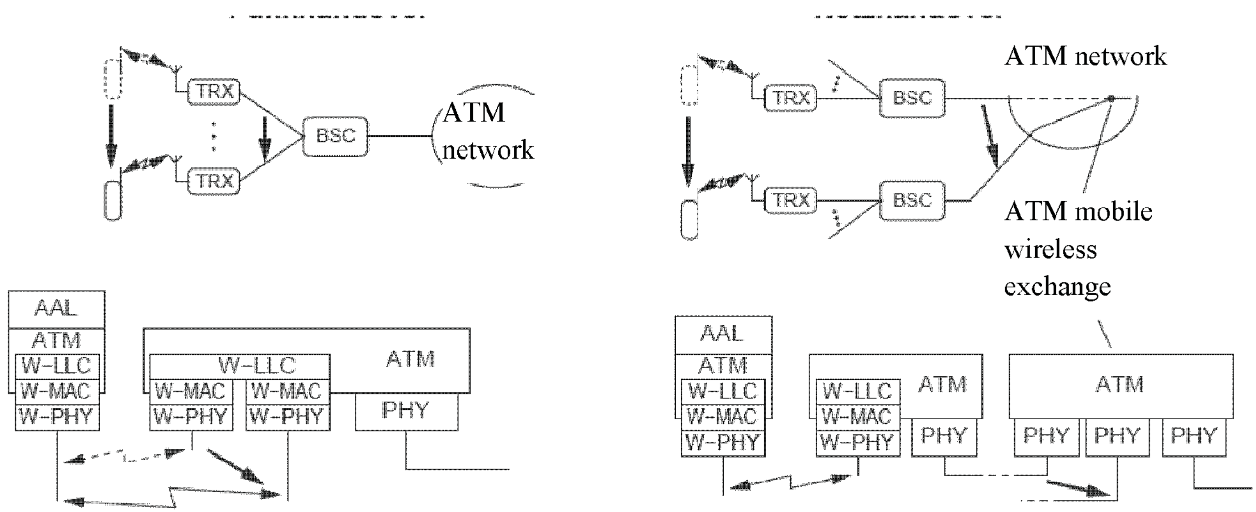


Figure 3.2: Handover to the ATM-wireless interface (wireless handover) and in the ATM-fixed network (network handover)

Within the scope of this work, the handover is not discussed in further detail. Detailed investigations about the network architectures and protocols for handover execution are found, for example, in (7, 35).

The technical data from the wireless interface are oriented to the recommendations of the wireless ATM group (RES10 WAG) of the European Telecommunications Standards Institute (ETSI) (26) and are summarized in table 3.1

Frequency band	5.2 GHz
Multiplex procedure	FDM
Access procedure	TDMA
Duplex procedure	TDD
Bandwidth of a frequency channel (carrier)	23.5 MHz
Gross data rate on a channel	50,000 ATM cells/s (= 20 Mbit / s)

Table 3.1: Technical data from the ATM wireless interface

Aspects of the frequency planning and procedure for the dynamic channel assignment are not considered. This allows for the isolated observation of individual wireless cells with a central base station and multiple wireless or mobile terminals.

3.1 The wireless cells as distributed ATM-multiplexers

A typical area of use for cellular ATM mobile wireless networks includes wireless local networks (Wireless Local Area Networks, W-LAN). Here it is desirable that through the wireless terminal in the area, it can provide the same services despite is possibilities (limited operating duration through battery controlled energy supply and lower data rates due to wireless transmission) as through ATM-terminals with a fixed network connection. In particular, all available ATM applications should be usable without changes, this means both can be used in wireless and wired terminals for the same services of the AAL.

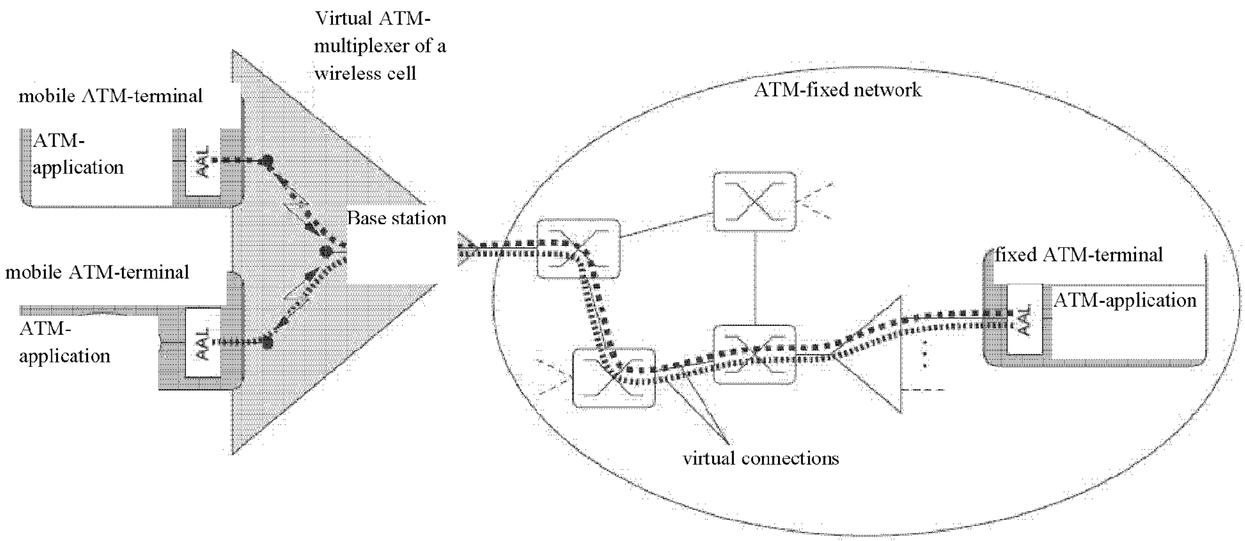


Figure 3.3: Inclusion of a cellular ATM wireless network into an ATM-fixed network

Figure 3.3 once again shows that the AAL-protocols are transport protocols with an end-to-end relationship, whose protocol instances are in the terminals. The transfer to the ATM wireless interface occurs within the ATM-layer based on individual ATM-cells, whereby the influences of the wireless interfaces of the service users on the ATM-layer (the instances of the AAL) remain hidden. This is distinguished in the following as a *transparent transfer* of ATM-cells. From a user view, the terminals of a wireless cell, which operate virtual connections through the base station, act as if they were connected with an ATM-multiplexer through a cable, see figure 3.4 above.

Thus, the wireless cell with its central base station and wireless terminal can be modeled as a distributed, virtual ATM-multiplexer, whereby the wireless interface is within the multiplexer, see section 3.4 middle part. In order to consider the individual service level requirements of the individual virtual connections, in addition to the protocols of the physical layer, protocols of the ATM-layer are executed as well.

On the side of the virtual multiplexer facing the terminal, there is a modified UNI-interface, which is distinguished with W-UNI. The modifications are only in regards to the control and management protocol planes. In order to guarantee data transparency, the user plane must be maintained without changes. The modifications in the control and management planes are required in order to manage the effects of the mobility, to register to the user and to allow for their influence.

Between the virtual multiplexer and the fixed network, there is an NNI-interface modified with M-NNI. In contrast to a normal NNI-interface, it must allow for the execution of handovers and the management of the network operating equipment required for this (7, 35).

Normally, by the W-UNI interface it deals with an internal interface within a terminal. In order to minimize the implementation expenses, in this case the AAL-layer can be set directly on the ATM-layer above the protocol plane of the wireless interface, see figure 3.4, transition from the middle to lower part.

The virtual ATM-multiplexer forms a distributed waiting system with transmission buffers in terminals (for the ATM-cells of the uplink) and the base station (for the ATM-cells of the

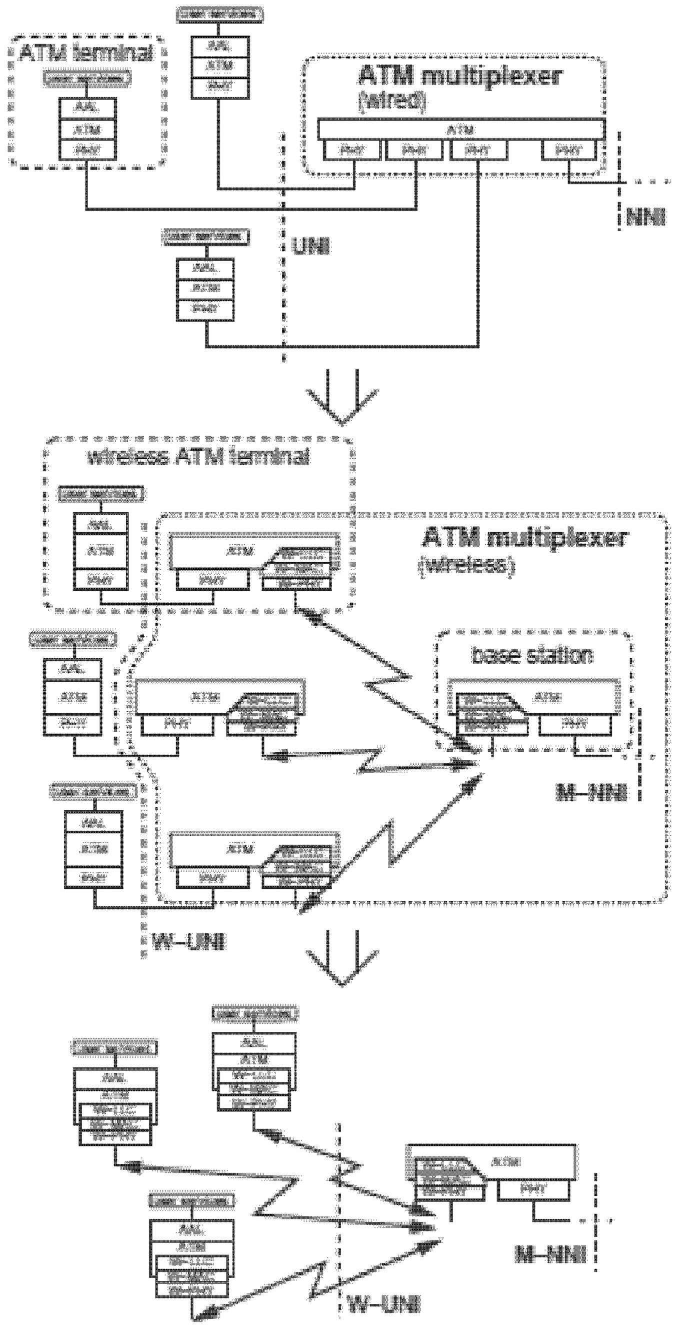


Figure 3.4: Implementation of a distributed (virtual) ATM-multiplexer within a wireless cell

downlink) and a control unit, called a *scheduler*, in the base station, which controls the transfer sequence of ATM-cells. As in cable-bound ATM-multiplexers with comparably low data rates (i.e. 20 Mbit/s (26)), the individual service level requirements only fulfill real-time oriented connections if the transfer sequence of the cells is controlled in the buffers based on their waiting times.

3.2 The protocol plane of the ATM-wireless interface

The wireless channel of the virtual multiplexer, in contrast to the fixed network, requires the additional observation of the wireless-specific aspects:

Wireless expansion: for example, bending, shading, reflections and multiple-path expansion

Channel access: coordination of the access to the mutually used wireless channel for the realization of the transfer sequence of the ATM-cells defined by the scheduler

Incorrect security: The unreliable transfer conditions on the wireless channel require the use of incorrect security procedures in order to fulfill the service class requirements of the individual virtual connections dependent upon the individual service classes.

Since by the usage of fiber-glass technology transfer errors cannot be completely hindered, an end-to-end error correction procedure must be used in the AAL-layer dependent on the service type and, on the other hand, in the ATM-layer the routing information is guaranteed in the cell heads through additional redundancy (Header Error Control, HEC), see figure 2.2.

For the real-time oriented CBR and VBR services, the AAL-protocols type 1 and type 2 are used. They provide their protocol data units (PDU) with a sequential number and test bits in order to recognize lost or incorrectly added ATM-cells. Optionally, through the usage of a FEC-procedure, bit errors can be corrected (13). If the bit error probability in the ATM-layer exceeds the ability to correct of the used code, which is the case on a wireless transfer path, the service level required by the user cannot be guaranteed by this procedure.

In the AAL-protocols type 3/4 and type 5, an ARQ-protocol is executed in the upper sublayers of the AAL (Service Specific Convergence Sublayer, SSCS), which is supported on the functions for the recognition of bit errors and cell losses of the lower AAL-sublayers (Common Part Convergence Sublayer, CPCS and segmentation and reassembly, SAR) (6). An efficient execution of this ARQ-protocol is possible according to (8) with a package loss probability of 10^{-3}. In order to maintain this package loss probability for packages of 1 kilobyte length, the bit error probability 10^{-7} may not be exceeded. The bit error probability of a wireless transfer path protected by the FEC-procedure is normally above this and is therefore too high for an efficient execution of the ARQ procedure in the AAL.

Thus, in order to reach the required service class on the wireless path, in addition to the error protection measures of the AAL, a security protocol (ARQ-protocol) will be used in the LLC sublayer directly on the wireless interface in order to provide transparency to the AAL. This deals with a service class specific

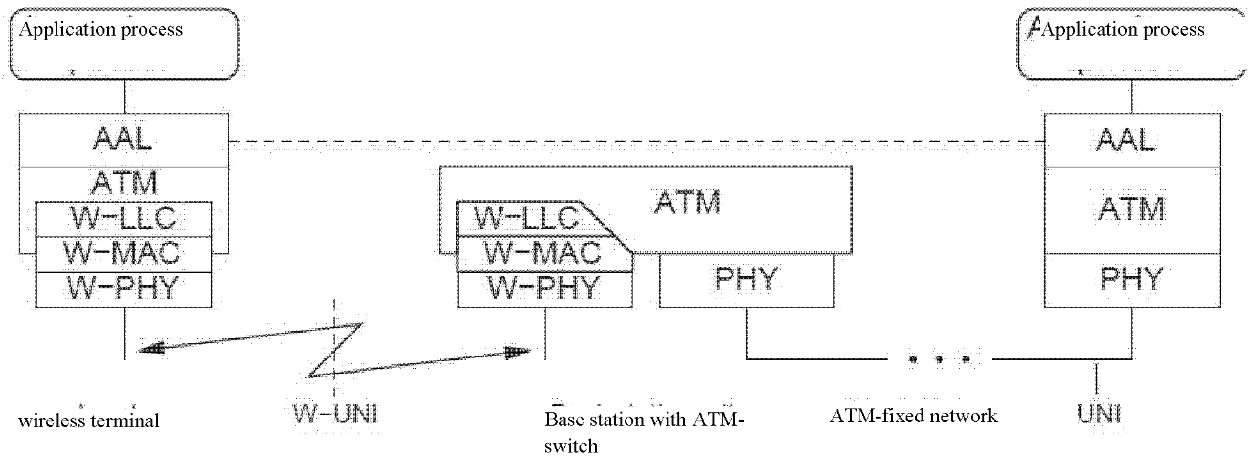


Figure 3.5: Protocol plane of the ATM-wireless interface

ARQ protocol, whereby through an individual service access point per ATM-service class in the LLC-sublayer, the expenses for the error control can be adjusted to the individual requirements of the individual virtual connection.

Figure 3.5 shows the resulting protocol plane, which contains a bit transfer layer, which considers the specialties of the wireless transfer (Wireless Physical Layer, W-PHY) and a security layer (Data Link Layer, DLC). The DLC layer consists of a sublayer for the coordination of the channel access (Medium Access Control, MAC) and from a sublayer, which controls the logical channels and contains the functions for the error control (Logical Link Control, LLC).

The MAC layer provides the scheduler with services, which they need to control the transfer sequence of the ATM-cells. For the coordination of the channel access, the MAC-layer executes a signaling protocol, which shares the situation of the time slots with the terminal in which it may send the ATM-cells through the uplink to the base station or in which it must receive ATM-cells from the downlink. Furthermore, it controls the transfer of the capacity requirements from the terminals to the base station in order to inform the scheduler about the connection-specific occupancy states of the transmission buffer in the terminal.

The connection-specific functions of the error control by the ARQ-protocols require the assignment of the LLC-sublayer above the multiplex function of the scheduler. Since a connection-specific error control is not designated in the ATM-reference model for fixed networks and thus, no LLC-sublayer exists, the remaining function of the security layer (service class control and multiplex function of the scheduler) has been moved to the lower part of the ATM layer for simplification of the protocol plane. On the side related to the fixed network, this is considered in that the lower part of the ATM-layer, which contains the scheduler, is replaced by the LLC-sublayer and parts of the MAC-sublayer.

The service level supporting measures that are being investigated in this work affect the complete DLC layer. In the LLC-sublayer, the efficient transfer of a receipt of the ARQ-protocol is observed. A system for the channel monitoring in the MAC-sublayer is investigated and the effects of these measures on the architecture of the scheduler are analyzed. Special wireless-specific FEC-procedures are combined with an ideal channel coding, thus, they are a task of the bit transfer layer and are not observed in this work.

CHAPTER 4

The Layers of the Protocol Plane and their Functions

After the structure of the protocol plane was derived in the previous chapter, the individual sublayers and their functionality will be defined now, whereby the concentration is on the service level control by the cell scheduler.

4.1 The operating strategies of the distributed virtual multiplexer

Before the protocols and functions of the individual layers will be detailed, the operating strategy of the distributed virtual multiplexers will first be explained, provided they affect the functionality of the protocol. While in the ATM-fixed network the operating strategies of the ATM-multiplexer are mainly geared towards avoiding cell losses through buffer excesses, the operating strategies of the distributed virtual multiplexers require a different observation of the wireless interface due to the comparably lower gross data rate (= 20 Mbit/s):

- For UBR-connections, no service level requirements are defined. Only their sequence must be maintained during the operation of the ATM-cells.
- ABR-connections are insensitive in regards to the transfer delays, that is why the algorithms developed for the fixed network multiplexer can be taken over without changes (i.e. the class of the weighted fair queuing algorithms (2)), which makes sure that the capacity available for these service classes is divided equally among the connections.
- For real-time oriented VBR and CBR connections, the transfer delay of the parameters to be determined is included under the service level aspects. Thus, with the operating strategy for these service classes, the minimization of the average waiting periods in the transmission buffers of the connection is in the foreground. For these service classes, the scheduler uses a date-oriented operating strategy (Earliest Due Date First, EDD), which is investigated in detail in (16, 21). Here the date T_{dd} of an ATM cell is defined as the sum of the arrival time of the cell T_a and the maximum allowed delay T_{dmax}:

$$T_{dd} = T_a + T_{dmax} \qquad (4.1)$$

A size deriving from this is the *date exceeding probability*, which describes the probability with which cells from a virtual connection exceed their schedule and are therefore rejected.

- The low-rate CBR connections, which only occupy a small portion of the channel capacity, are easier to treat (speech services with 64 kbit/s, video telephony with 128 kbit/s), if they are subject to all other service classes, see (22, 30).

The service-class specific static priorities[1] result from this for the control of the transfer sequence of the ATM-cells:

$$P_{CBR} < P_{VBR} < P_{ABR} < P_{UBR}. \tag{4.2}$$

In the following, the UBR service classes are used representatively for the time-uncritical service classes of ABR and UBR.

4.2 The MAC Protocol and its Services

In the MAC-layer of the system, the reservation-based *dynamic slot assignment* (DSA++) MAC protocol (21) is used, which coordinates access to the wireless channel.

The MAC layer establishes a MAC-connection for every registered terminal, which is accessible on the MAC-service access point (Service Access Point, SAP). In the MAC-SAP of the basis station (BS-MAC-SAP), a connection end point (CEP) is set up for every MAC connection. Its address (CEP-Identifier, CEP-Id) is labeled as a MAC-Id and used within the wireless cell as a short address for the registered terminal. In the MAC-SAP of the registered wireless terminal (WT-MAC-SAP), the MAC-connection ends in the only connection end point with MAC-Id=1.

On MAC-connections, there are two data transfer services (data service) for long and short service data units (SDU), which use the two logical channels of *data channel* (DCH) and *request channel* (RQCH). The DCH-data service is used for the transfer of ATM-cells through uplink and downlink. A DCH-SDU allows for the transportation of an ATM-cell and additional protocol control information. The RQCH-data-service transfers the RQCH-SDUs from the terminals through the uplink.

At the connection end point 0 of the MAC-SAP, a special permanent signaling channel is available, the Global Control Channel (GCCH) (24). It serves for the transfer of wireless signaling messages for wireless and mobility specific functions like wireless calls, registration and handovers. On the downlink, it is used as a shared transmission channel and the random access occurs on the uplink. In this work, signalizing aspects are neglected in so far as it is assumed that the terminals have run through a registration procedure, which sets up a MAC-connection allocated to them.

For the coordination of the channel access, the DSA++-protocol groups timeslots to so-called *signalizing periods*, see figure 4.1. A signaling period is implemented through a central signaling message, the period Ctrl PDU (*Period-Control-Protocol-Data-Unit*), followed by three phases with timeslots for down-DCH-PDUs, Up-DCH-PDUs and RQCH-PDUs (see table 4.1).

The timeslots of the down DCH and up-DCH-phases are reserved respectively for a channel. The accesses to the RQCH-timeslots are controlled through a separate RQCH-access protocol, which is described and evaluated in (21). It uses a reservation-free access procedure with random access, which allows for the direct usage of the RQCH-service.

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[1]Small number values stand for high priorities, as is normal in the traffic theory

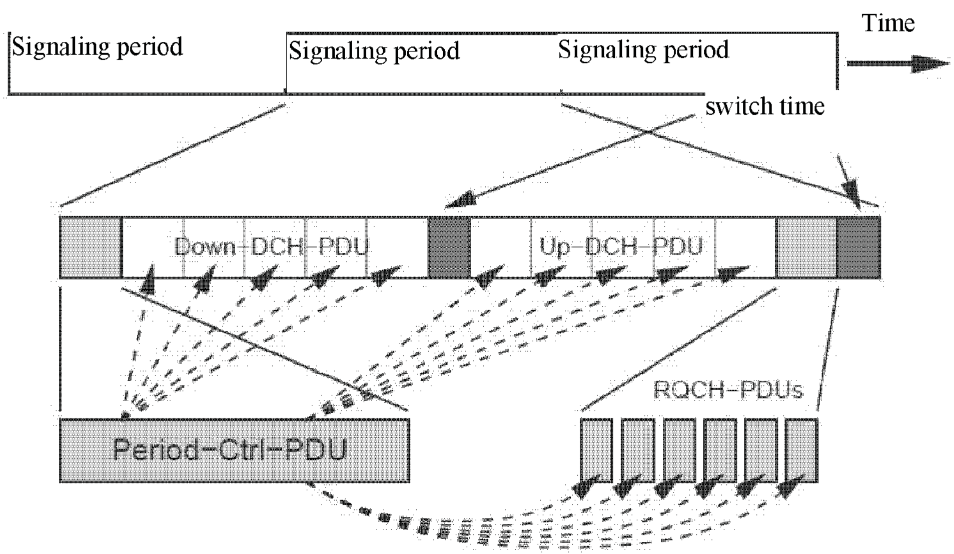

Figure 4.1: Construction of the signaling periods in the DSA++-Protocol

Type	Direction	Content	Usage
Period-Ctrl-PDU	Downlink	See tab 4.2	Signaling of timeslot reservations
Down-DCH-PDU	Downlink	Type (2 bit) MAC-Id (6 bit) Down-DCH-SDU (55 byte)	Transfer of a downlink DCH-SDU
Up-DCH-PDU	Uplink	Type (2 bit) MAC-Id (6 bit) Up-DCH-SDU (57 byte)	Transfer of an uplink DCH-SDU
RQCH-PDU	Uplink	Type (2 bit) MAC-Id (6 bit) RQCH-SDU (4 byte)	Transfer of a RQCH-SDU

Table 4.1: PDUs from the DSA++-MAC-protocol

The length of the phases of a signaling period and the reservations of their timeslots is signalized through the Period-Ctrl-PDU. These reservations contain the MAC-Id of the assigned channels for every timeslot of the down-DCH or Up-DCH phase. The signaling of the number of RQCH timeslots and the corresponding access rights occurs through the generic RQCH signaling field, whose structure depends on the RQCH-protocol being used. Finally, the Period-Ctrl-PDU contains a field in which LLC-PDUs (i.e. receipts) can be sent together with their MAC-IDs (see table 4.2). According to (21), it is assumed that 338 bit are available for the Period-Ctrl-PDU. This value results from the length of a Down-DCH-

PDU (440 bit) minus the expense for an increased error protection (approx.. 30%). This results in the following for the maximum number of reservations:

$$N_{DD} + N_{UD} = \frac{(338 - 2 - L_{RQCH} - 2 * 6 - 144)\text{bit}}{6\text{bit}} \qquad (4.3)$$

The theoretical maximum number of DCH-reservations $N_{DCH_{max}}$ with empty RQCH-field ($L_{RQCH} = 0$) amounts to 30 reservations.

Field	Length	Usage
Type	2 bit	distinguished Period-Ctrl-PDU
RQCH-signaling	L_{RQCH}	dependent on the RQCH-protocol
N_{DD}	6 bit	Number of down DCH-PDUs
Down-DCH-reservation	N_{DD} x 6 bit	Field from N_{DD} MAC-IDs
N_{UD}	6 bit	Number of Up-DCH-PDUs
Up-DCH-reservation	N_{UD} x 6 bit	Field from N_{UD} MAC-Ids
Broadcast field	144 bit	6x: LLC-PDUs (18 bit) + MAC-Id

Table 4.2: Structure of a Period-Ctrl-PDU

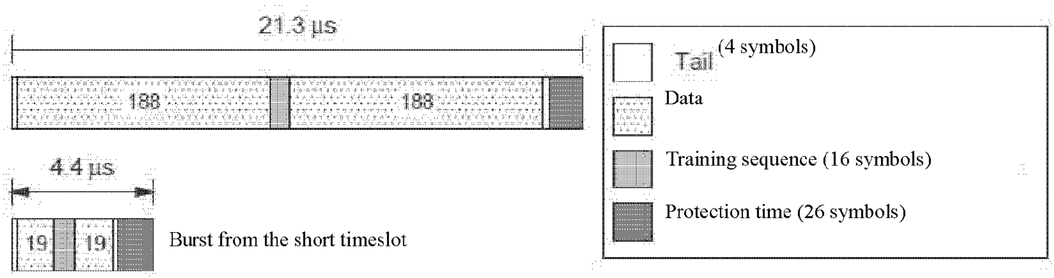

Figure 4.2: Structure and length of the physical burst of the mobile broadband system (MBS)

4.2.1 Length of the timeslots and physical layer

The transfer of the MAC-PDUs occurs through bursts from the physical layer, which are assigned to the timeslots. The length of the bursts and thus, the length of the timeslots is determined by the protocols and algorithms of the bit transmission layer and the modem. Realistic values for the length ratio of long DCH- to short RQCH timeslots are between 3 and 8. The functionality of the DSA++-protocol is primarily independent of the concrete implementation of the model, which is why, based on the structure and the length of the physical bursts used in the Mobile Broadband System (MBS) (figure 4.2) (24) and the gross data rate of a frequency channel of 50,000 ATM-cells per second, the following lengths are accepted:

Type	Duration/value
long DCH-timeslot	$T_{slot} = T_{DCH-Slot} = 20\ \mu s$
short RQCH-timeslot	$T_{RQCH-Slot} = 5\ \mu s$
Ratio of DCH to RQCH timeslots	$T_{Slot} = T_{DCH-Slot} / T_{RQCH-Slot} = 4$
Transceiver switch time	$T_{TaR} = 1.25 \mu s$ (23)

Table 4.3: Timeslot lengths

The difference between the lengths of Up-DCH-PDU and Down-DCH-PDU is neglected here. The transceiver switch time T_{TxR} between the timeslots of the uplink and the downlink is required in order to reduce the energy of the transmission signal from the delivery to the reception in the high-frequency part, which can have a sound up to 100 dB higher than the reception signal.

4.2.2 Signalizing of capacity requirements

For the reservation assignments, the ATM-cell scheduler in the base station must be adequately informed about the occupancy of the waiting buffer in the terminal, which happens through the signalizing of capacity requirements through the uplink. Here the following requirements exist for the signaling protocol:

Punctual signalizing: The guarantee of the required maximum delays $T_{d\max}$ from real-time oriented services is only possibly with the punctual signalizing of the new arrivals from ATM-cells.

Low capacity consumption: The signaling occurs in competition to ATM-cells: channel capacity proven through signaling leads, under circumstances, to higher waiting times for ATM-cells.

Adequately precise formation of the capacity requirements: an illustration that is not precise enough for the occupancy states of the transmission buffer can lead to the disappearance of channel capacity if more timeslots were reserved than required or increases delays in the case of an under-reservation of the ATM-cells.

By the signaling of capacity requirements, the following sub-aspects must be observed:

- Coding of the waiting buffer occupancy depending on the service class
- Determination of the signaling frequency or the signalizing points
- Type of transfer from capacity requirements

The coding of the waiting buffer occupancy or the capacity requirements of the terminal occurs specific to the service, determined based on the algorithms used in the scheduler. Since the MAC-protocol only differentiates between terminals, but the scheduler between virtual connections in contrast, the capacity requirements of all connections of the same service class are summarized and

and are coded in a generic data structure of about 2 bytes, the *dynamic parameters*[2]. The capacity requirement of a terminal is described by a group of dynamic parameter objects in which one object is contained for each service class. In order to send a capacity requirement message, a terminal selects the dynamic parameter of the service class with the highest static priority for which the capacity is required.

VBR service class: since the ATM cells of the VBR service class are transferred in the sequence of their importance, the dynamic parameter of the VBR-service class contains the remaining lifespan T_{r1} of the most urgent VBR-ATM cell and the number Z of cells, whose remaining lifespan is at most the maximum length of a signaling period $N_{DCH\,max}$ x T_{Slot} greater than T_{r1}, see figure 4.3. The planning horizon is adequate under the aspect of the maximum delay, because with every delivered ATM-cell, new dynamic parameters are transferred, which inform the base station about the other capacity requirements and can be reacted to in the next signaling period. However, through this mechanism it is possible that ABR-cells are transferred before VBR-cells, so that no capacity for these was requested and the available capacity of the signaling period is not completely occupied through CBR and VBR cells.

CBR-service class: The dynamic parameters for the CBR service class are structured analog to those of the VBR-service class. An optimized procedure, which is not considered here, uses the deterministic temporary arrival times of the CBR cells in order to extrapolate the time of the next arrival in the base station. The dynamic parameters serve for the synchronization of the base station to the arrival process in the terminal. In the case of an incorrect extrapolation, the terminal must transfer its dynamic parameters explicitly to the base station. A corresponding protocol was introduced and investigated in (22, 30).

ABR-service class: The scheduling procedures for the ABR-service class are an object of the current investigations. It is imaginable, for example, that in addition to the pure capacity requirement, control information for the operating strategies is transferred as well.

UBR service class: The dynamic parameters of the UBR-service class contain the number of waiting UBR-ATM-cells.

The DSA++-MAC protocol knows of two possibilities for transferring the dynamic parameters:

- i
  n DCH-timeslots piggyback to the ATM-cells
- i
  n short RQCH-timeslots through random access or through the basis station with help from polling

The transfer occurs dependent on the reservation state of a terminal. Figure 4.4 shows the corresponding state transition diagram. In the state *empty run*, the waiting buffer of the terminal is empty so that no dynamic parameters are delivered. After the arrival of an ATM-cell, the terminal changes to the state *Request* (state transition 1) and tries to transfer its dynamic parameters through random access to

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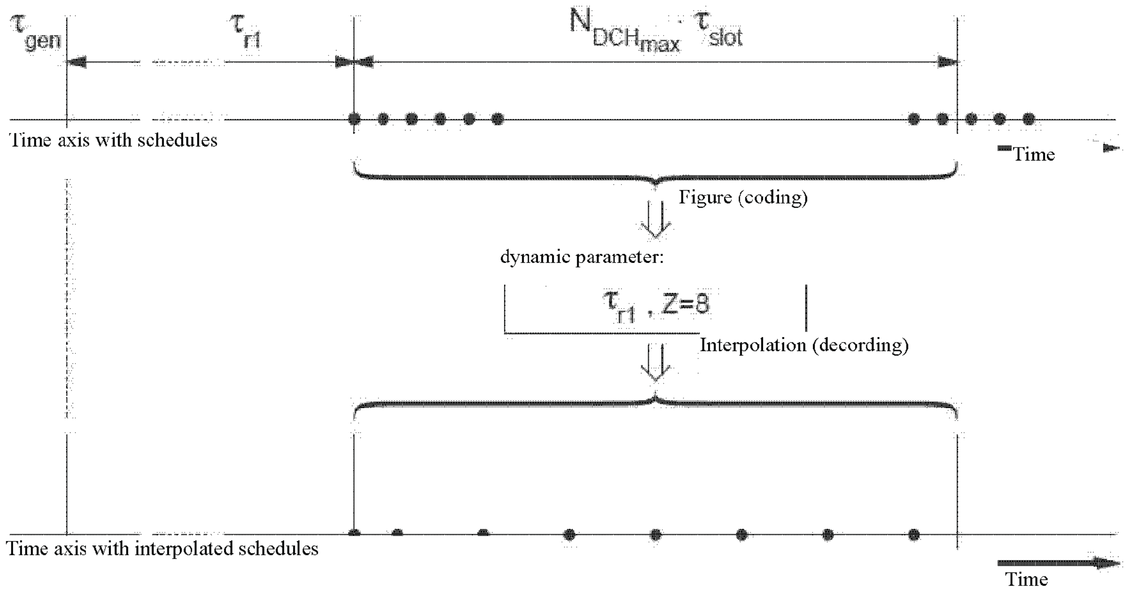
[2]The name *dynamic parameter* describes the dynamic character of the capacity requirement illustrated for it in difference to the static connection parameters and ATM service level parameters.



T_{gen} Generation point in time of the dynamic parameter

T_{r1} Remaining lifespan of the most urgent ATM-cell

$N_{DCH\ max}$ x T_{slot} Maximum period length (planning horizon)

Z Number of ATM-cells in the planning horizon

Figure 4.3: Coding and decoding of the CBR/VBR dynamic parameters

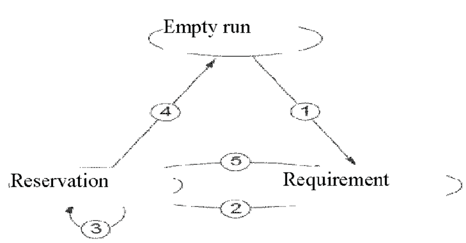


Figure 4.4: Reservation states of a terminal

shot timeslots of the RQCH. After successful transfer, the terminal changes the state into *reservation* (2) and is served by the scheduler depending on the urgency of the ATM-cells. By the transfer of an ATM-cell into a reserved DCH-timeslot, the scheduler constantly shares the current capacity requirements through dynamically transferred parameters 3. If during the transfer of an ATM-cell there are no other requirements, no dynamic parameters will be transferred any more, whereby the base station signalizes the change of the terminal into the *empty run* state 4.

A special case illustrates the simultaneous operation of multiple virtual connections of different service classes. The terminal requested a lower-prioritized service class (i.e. ABR) channel capacity and is therefore in the *reservation* state; upon arrival of ATM-cells from a high-prioritized service class (i.e. real-time VBR), the capacity requirement can change so that the next reserved timeslot from the base station cannot be waited for in order to transfer the new dynamic parameter to the ATM cells of the lower-prioritized service class. Instead, the *request* state is returned to (state transition 5) and a new transfer of the dynamic parameter is executed in the RQCH.

The MAC-instance of the base station follows the reservation state of the terminal in order to estimate the number of terminals, which transmit in the timeslots for the random access. Based on the received dynamic parameters, the base station can recognize the state transitions 2, 3 and 4, however, a transition to the *request* state cannot be determined. Through the incorrect transfer of dynamic parameters, a terminal can change into the *reservation* state without the base station registering this. The terminal must recognize such a situation and return to the *request* stage. To do this, the base station signalizes in every Period-Ctrl-PDU (in the field for the RQCH signaling) the priority of the ATM-cell, which the scheduler assigned to the last timeslot of the current signaling period. A terminal can, if applicable, recognize through the comparison of this priority with its own capacity requirements that by the timeslot assignment, despite an adequately high priority, it was not considered and the consequence of this is the loss of the last transferred dynamic parameter. In this case, the transfer of the dynamic parameter will be immediately repeated.

4.3 The structure of the LLC layer

The LLC layer is illustrated in figure 4.5 for the terminal and in figure 4.7 for the base station. In addition to the ARQ instances that execute the ARQ-protocols corresponding with the service classes, it contains parts of the scheduler. If multiple virtual connections from one or different service classes are available, a corresponding number of ARQ-instances are distributed on the service class entities and are operated parallel to each other. The address of the ARQ-instance occurs through ARQ identification numbers (ARQ-Id), which are unique within the LLC-instance of a terminal. A personal ARQ-instance is required for every virtual connection of real-time oriented service classes in order to allow the scheduler the schedule-oriented operation of ATM-cells corresponding with their connection-specific service class requirements.

With parallel ARQ instances, the instance with the most urgent ATM-cell must not automatically transfer the most urgent receipt. Thus, information and receipt field of an ARQ-frame are filled by different ARQ instances. The information (I) frame of the ARQ instances does not contain a piggyback receipt, but rather only the content of an ATM-cell. Receipts and I-frames are distinguished as ARQ-PDU and generated independent of each other, see section 5.1.

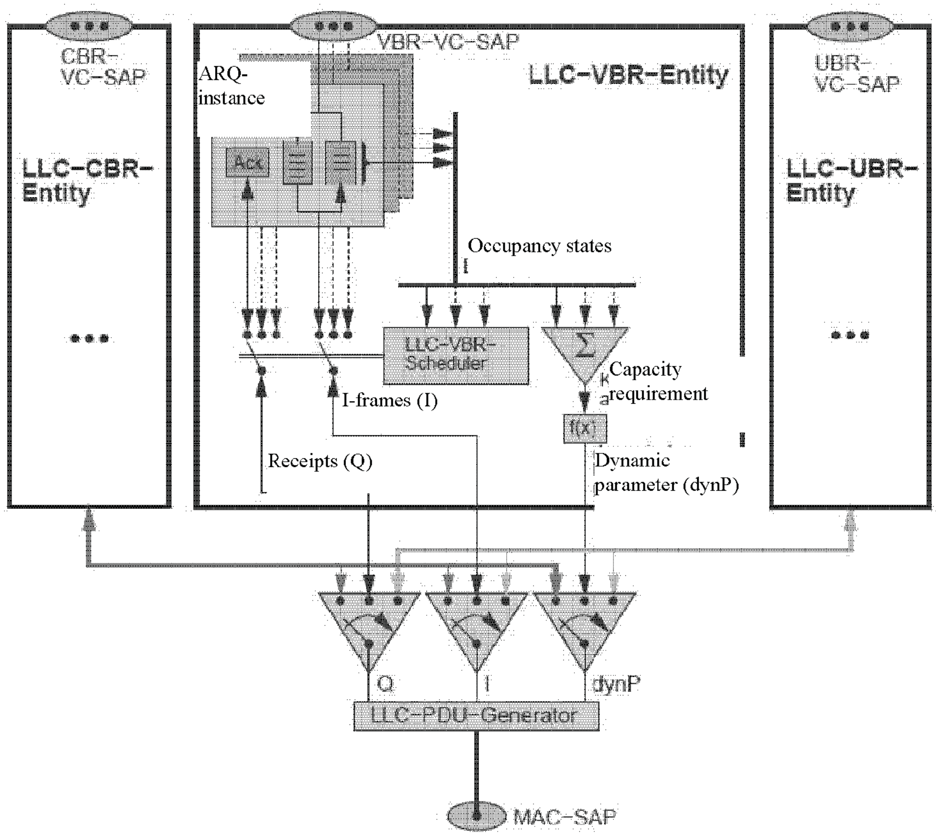


Figure 4.5: LLC-Entities of the Terminal

Information frame	ARQ-Id	N(S)	P-Bit	Usage data, 51 byte	53 byte
(I-PDU)	8 bit	6 bit	1 bit	(ATM-cell without HEC and VPI)	
Receipt (Ack-PDU)	ARQ-ID	Type	N(R)	P/F-bit	18 bit
	8 bit	3 bit	6 bit	1 bit	
Dynamic parameter	Service cl.		Requirement		
(DynPara-PDU)	2 bit		2 byte		18 bit

Figure 4.6: Structure of the ARQ-protocol data units and the dynamic parameter

The structure of the ARQ-PDUs and the dynamic parameters are shown in figure 4.6. Since a FEC-procedure is executed in the physical layer for error correction and recognition, the transfer of the header-error-control-field (HEC) from an ATM-cell will be waived in the I-frame. The virtual path address (VPI) must also not be transferred, because it can be reconstructed from the ARQ-Id[3].

[3]The VCI cannot be reconstructed from the ARQ-Id and must be transferred, because by the usage of a virtual path, the network nodes are not informed about the setup of a virtual connection.

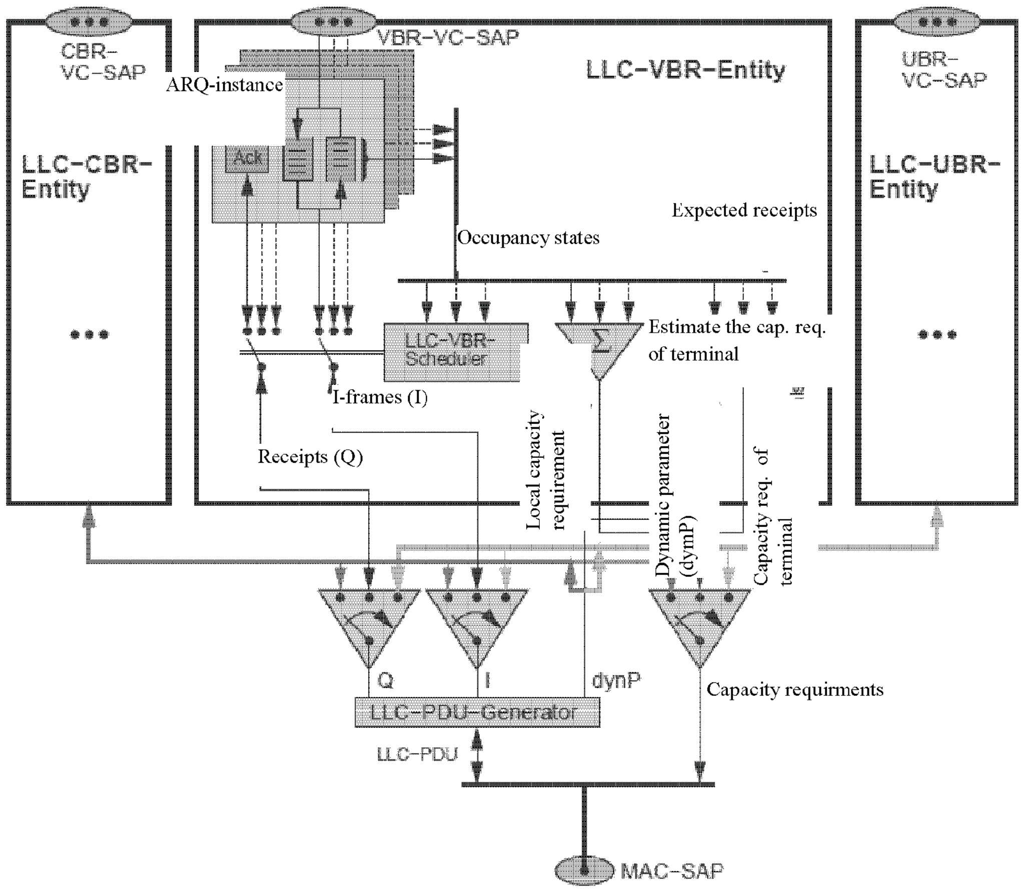


Figure 4.7: LLC-entities of the base station

4.4 The cell scheduler

In the security layer of the protocol plane, the function of the cell scheduler is realized for the distributed virtual multiplexer, whereby the following basic conditions must be considered:

- Due to the reservation-based MAC protocol, which announces the usage of the timeslot of the wireless channel at the beginning of a signaling period by a signaling message, the scheduling procedure is divided into a reservation phase and a transfer phase, this also resulted from a distributed assignment of the scheduler to the MAC and LLC sublayer.
- In the reservation phase, the scheduler coordinates the access of the terminal and the base station to the mutually used wireless channel and reserves timeslots corresponding with the capacity requirements. Hereby the scheduler decides between ATM-service classes and virtual connections, in contrast the MAC-protocol only differentiates DCH-connections.
- The scheduler in the base station cannot directly query the occupancy states of the transmission buffer in the terminal. For this, it uses a service from the MAC-protocol, which transfers the capacity requirements of the terminals so that they can be considered in the base station through the scheduler.

- Conventional ARQ-protocols transfer information (I) frames (here an ATM-cell in the information field) with piggyback receipts and short monitoring frames with receipts. With asymmetric traffic, receipts can often not be transferred piggybacked to I-frames or ATM-cells. The scheduler must therefore consider the transfer of ATM-cells and receipts.

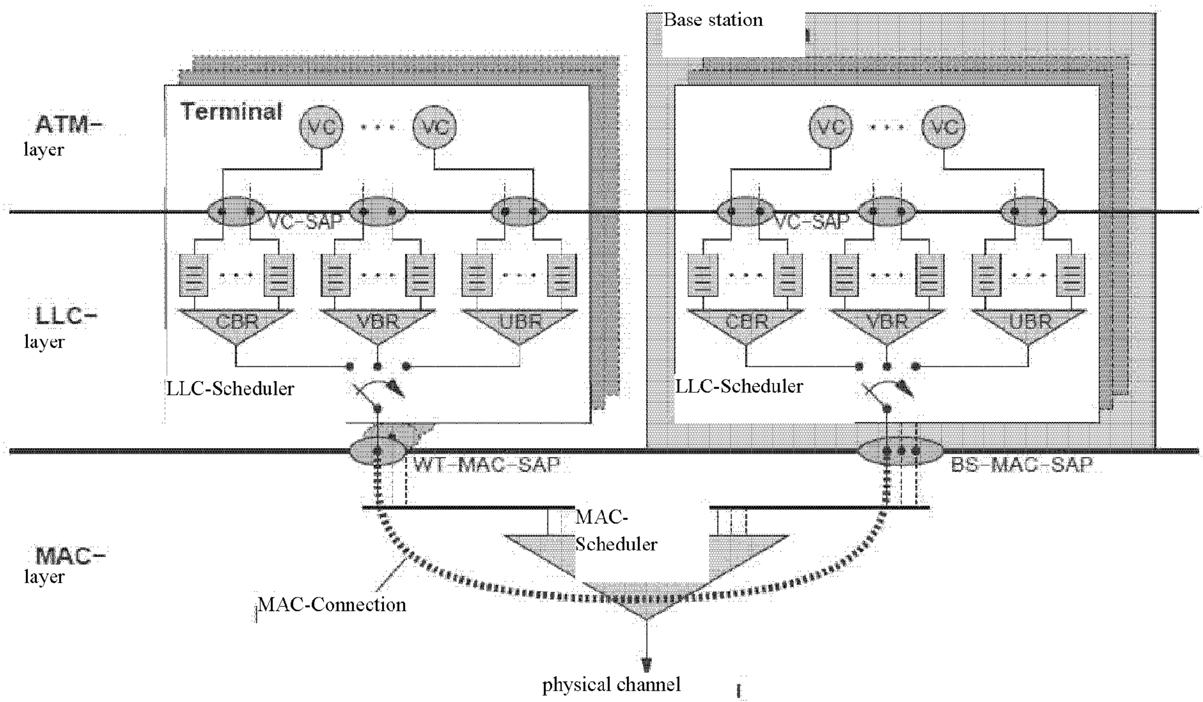


Figure 4.8: Division of the schedulers on the MAC and LLC layer

Figure 4.8 shows the division of the scheduler to the sublayers. The lower level, the MAC-scheduler, is scheduled to the MAC-layer and decides from or to which terminal an ATM-cell is transferred. The upper level, the LLC-scheduler, is realized by the LLC-layer and by the announced terminal, it selects the virtual connection, which delivers the ATM-cell to be delivered.

4.4.1 The reservation phase of the scheduler

During the reservation phase of the scheduler in the MAC-entity of the base station, the transfer sequence is determined for the DCH-SDUs of the next signalizing period. The message sequence chart (MSC) in figure 2.9 displays the process. In the base station, the MAC-entity from the LLC-entity queries for every MAC-connection the current capacity required for DCH-SDUs and this is for downlink (service primitive BS-Capacity.Indication) and the uplink (service primitive WT-Capacity.Indication). With the service primitive BS-Capacity.Response, the LC-entity answers for the personal downlink capacity required and WT-Capacity.Response for the uplink capacity required for the terminal. The personal capacity requirements are calculated by the LLC-scheduler. The capacity required for the terminal is determined from the capacity requirements saved in the base station.

The number of timeslots for up and downlinks is determined during the reservation phase of the scheduler. Here the DCH-SDUs compete against each other from the up and downlink, this means the number N_{DD} and N_{UD} results from the respective capacity required and is limited by the capacity of the period-Ctrl-PDU, see table 4.2 and comparison (4.3). If fewer DCH-SDUs are to be transferred, as signalized at a maximum,

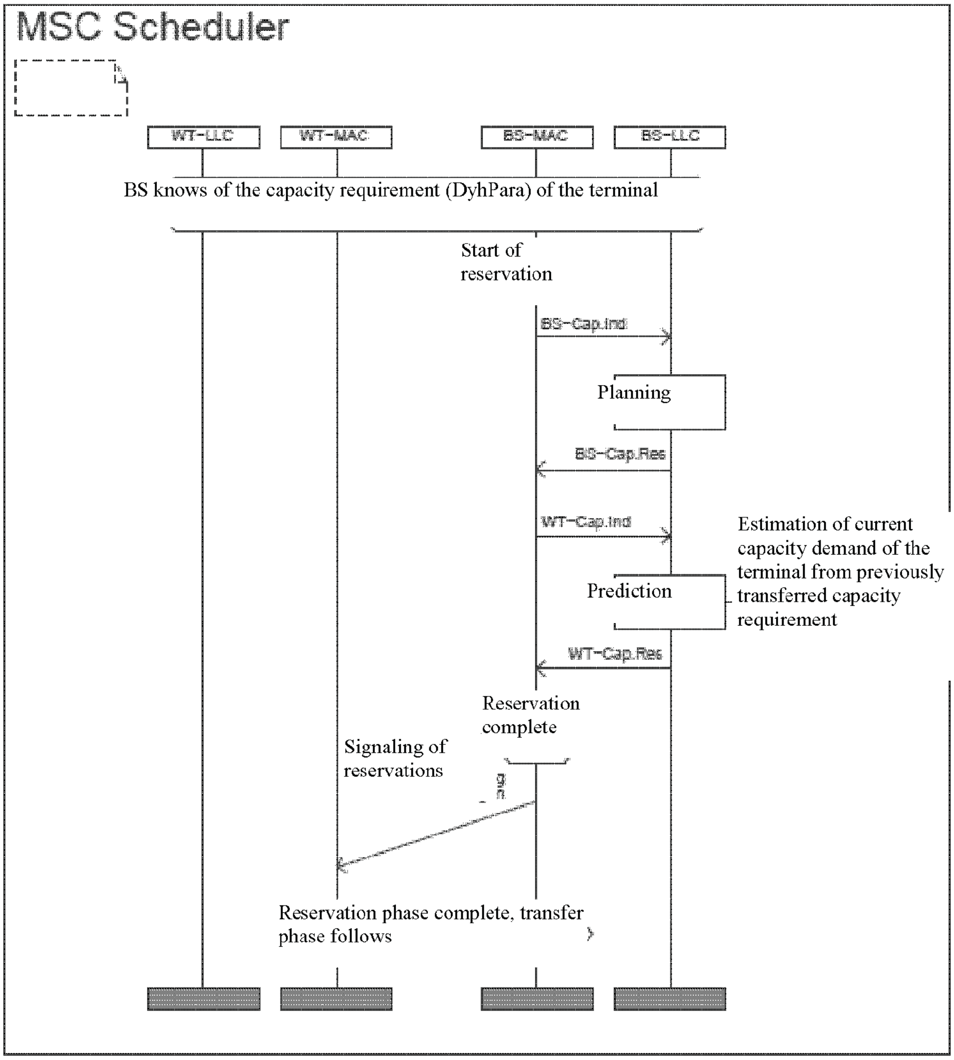


Figure 4.9: The reservation phase of the MAC-scheduler of the base station

parts of the DCH reservation fields remain unused and the signaling period is shortened correspondingly.

4.4.2 The transfer phase of the scheduler

In the base station, an instance of the LLC scheduler is created for every registered terminal and connected with the connection end point in the MAC-SAP, through which the MAC connection to the terminal is available, see figure 4.8.The LLC scheduler is composed of an entity per service class, between which it is selected with the static priorities (see comparison 4.2), see figure 4.5 and 4.7. The entities have a comparable structure, which is illustrated as an example provided the VBR-entity. The lower part of the VBR entity contains the LLC-VBR scheduler and functions for the signaling and management of the capacity requirements of the terminal. The upper part contains an ARQ instance for every virtual connection (Virtual Channel, VC), which is connected with a connection end-point in the VBR-VC-SAP. The ARQ-PDUs are generated independent of each other and first added to LLC-PDUs below the LLC-scheduler.

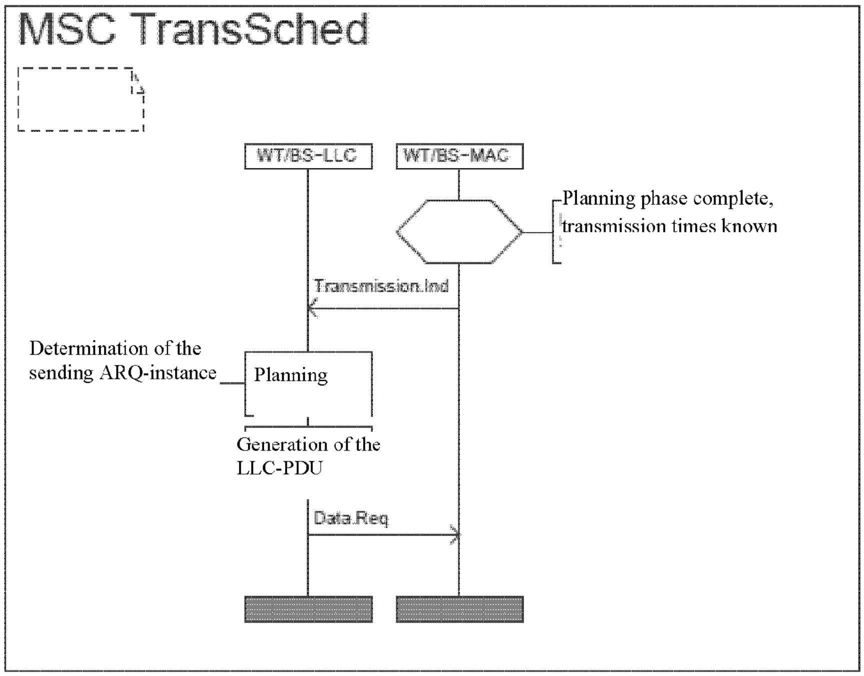


Figure 4.10: Determination of transmission-entitled ARQ-instance with known transmission time, known MAC-Id and transfer direction

The LLC-scheduler determines the ARQ instances with the currently most urgent ATM-cell and the most urgent receipt. Additionally, the current capacity requirement of all ARQ-instances is determined and characterized by the parameter, which determines the number and importance of the ATM-cells and receipts waiting to be transferred. This result is also used in order to

- inform about the current capacity requirement of an LLC instance in the base station during the reservation phase of the MAC-scheduler, see figure 4.9,
- determine the transmission-entitled ARQ-instance in the base station and the terminals during the transmission phase of the MAC-scheduler with a known transmission time, known MAC-Id and transmission direction, see figure 4.10,
- share the base station of the capacity requirement of a terminal, see figure 4.11.

The VBR-entities and base stations are only different in the management of the capacity required for the terminal. A terminal contains a coding function ($f(x)$ in figure 4.5), with which it forms its current capacity requirement for the dynamic parameters, see section 4.2.2. The dynamic parameters must be delivered punctually with a DynPara-PDU either piggyback to an I-frame and a receipt through the DCH or together with a receipt about the RQCH. In the base station, the respectively last dynamic parameters are saved. During the reservation phase of the MAC-scheduler, the current capacity required of a terminal

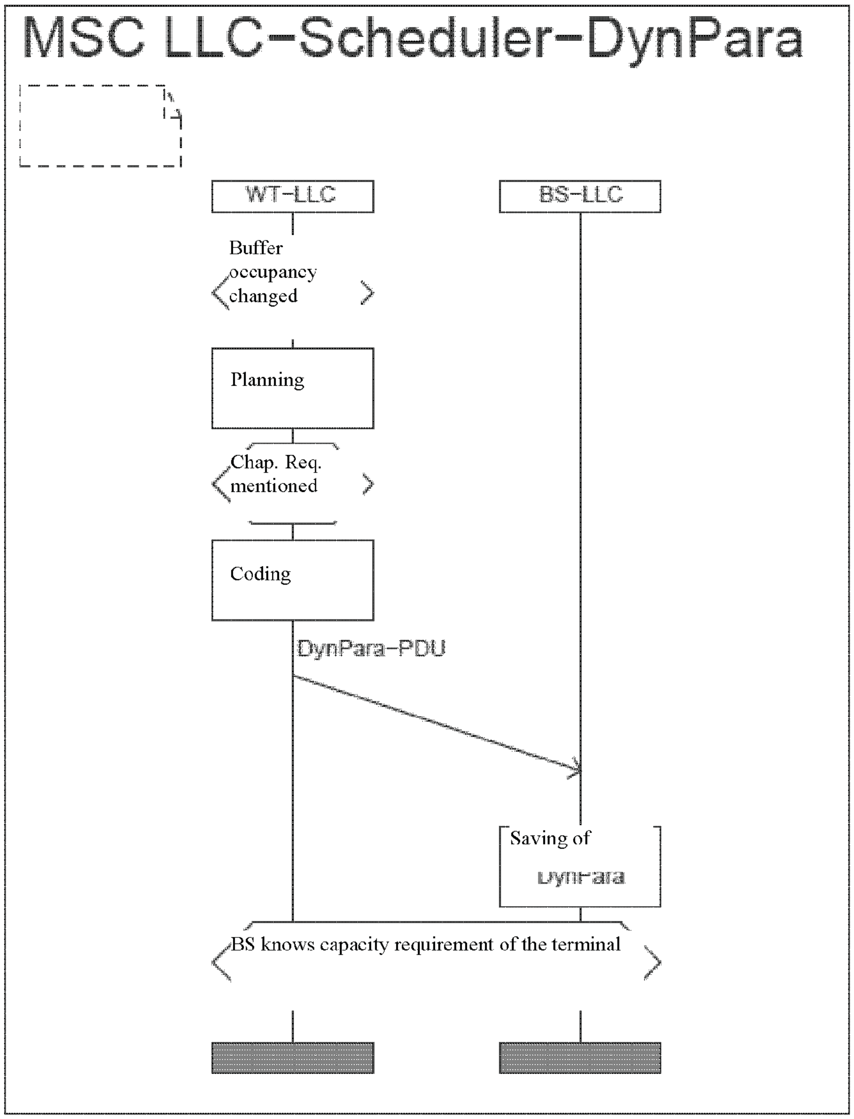


Figure 4.11: Transfer of capacity requirements of a terminal to the base station

is estimated through a prediction algorithm, in which the dynamic parameters are extrapolated to the respective point in time.

Below the service class entities, the PDUs or capacity requirements are selected corresponding with the static priorities and ARQ.PDUs and DynPara-PDUs are summarized to LLC-PDUs. Depending on the transfer service used for the MAC-connections (uplink/downlink DCH, RQCH), the LLC-PDUs have different lengths, see figure 4.12. The LLC-PDUs of the uplinks transport instead a DynPara-PDU. With the LLC-PDUs for the DCH, the first bit is used to decide if instead of the I-PDU, up to 24 other Ack-PDUs are transferred. This allows for the simultaneous delivery of multiple receipts of the same or different ARQ instances. Finally, it is possible in the base station to transfer receipts (Ack-PDUs) directly to the MAC-layer, in order to begin the Period-Ctrl-PDU in the broadcast field.

Down-DCH-PDU	I-PDU		Ack PDU		55 byte
Down-DCH-Ack-PDU	Ack PDU	Ack PDU	… up to 24		55 byte
Up-DCU-PDU	I-PDU	Ack PDU	DynPara PDU		57 byte
Up-DCH-Ack-PDU	Ack PDU	Ack PDU	… up to 24	DynPara PDU	57 byte
RQCH-PDU	Ack PDU	DynPara PDU			36 bit

Figure 4.12: Protocol data units of the LLC layer

CHAPTER 5

The SR / D-ARQ Protocol

The obtainable service level for a connection is determined by the measures used for error control. This applies in particular for wireless transfer paths, because wireless media has a lower transmission level than wired media. After a short introduction of the procedure used for error control and the general functions of ARQ-protocols, the investigated and evaluated *Selective Reject with Discarding* (SR/D) ARQ-protocol will be introduced for the real-time-oriented service classes. This ARQ-protocol, which is executed in the LLC-layer, see section 4.3, allows for the adaptation of the effort for the error control to the service level requirements of the individual virtual connection.

5.1 Measures for error control

There are two different types of error control procedures:

Forward error correction (FEC):
Through the systematic insertion of redundancy to the usage data by the sender, the recipient is able to recognize incorrect data blocks and to correct bit errors.
Automatic transfer repeat:
By the ARQ-procedure (Automatic Repeat Request, ARQ), the recipient recognizes the incorrect data blocks based on a checksum and requests a new transfer through a reverse channel. In order for the recipient to recognize which data blocks must be resent, the blocks receive a sequence number. This number also allows for the recognition of lost data blocks. In contrast to the FEC-procedure, the received data blocks must be logged here, which results in additional traffic on the return channel.

From the coding theory, it is known that with a predefined quantity of added redundancy, the number of correctable bit errors is less than the number of recognizable bit errors. On the other hand, the ARQ-procedure burdens the return channel with logs. Hybrid procedures – combinations from FEC and ARQ – limit the redundancy to be added and lower the number of transfer repeats.

The basic functions of ARQ-protocols will be introduced in the following section provided the Go-Back n (continuous) and the selective repeat (SR) ARQ protocol. Here the term “frame” is used for the data blocks. Frames that transfer user data are called information frames (I-frames). Frames that only contain a receipt are called receipt or monitoring frames (supervisory frames).For matters of simplification, it is assumed that all occurring bit errors are recognized and that the channel retains the sequence of the delivered frames, thus, the frames cannot pass each other on the channel. This requirement is provided by the wireless channel considered in this work. For more detailed illustrations of the ARQ-protocols, see for example (9, 10, 33)

5.2 Back-up protocols

Back-up protocols were developed in order to fulfill the following tasks (33):

- Recognition of transfer errors up to a very small remaining error rate
- By recognized transfer errors, no loss, exchange or doubling of data blocks
- Support of normal network structures like point-to-point, point-to-multi-point and ring through a single protocol

5.2.1 Go-Back *n* (continuous) ARQ

The Go-Back *n* or continuous ARQ-protocol is the most distributed ARQ-protocol and is used, for example, in the standard HDLC (High level Data Link Control procedure) according to ISO (11).

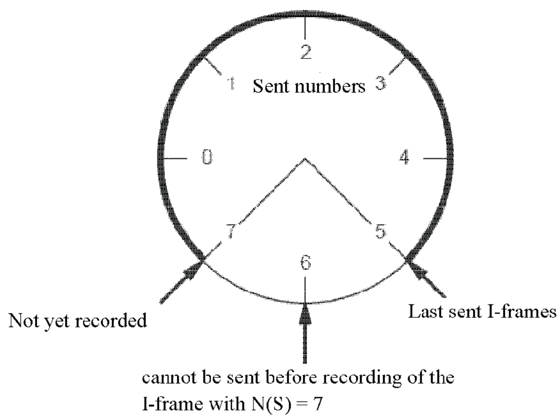


Figure 5.1: Transmission window with module 8 from the Go-Back *n* ARQ-protocol

With the Go-Back *n* ARQ-protocol, up to *n*I-frames can be delivered after each other before a recording must be waited for. In this case, we are speaking of a window mechanism with the size *n* (see figure 5.1). For controlling of the window, the transmitter has two internal variables with sequence numbers: SN_{min} contains the sequence number of the last I-frame requested by the recipient and SN_{max} the number of the last delivered I-frame. Here $SN_{min} \leq SN_{max} \leq SN_{min} + n$ must be fulfilled. After delivery of the I-frame with the number $N(S) = SN_{min} + n - 1$ must be waited for on a receipt, because the window has closed. After any final time limits, the I-frames are repeated from SN_{min} to $SN_{max} - 1$. With the receipt of a record with $SN_{min} \leq N(R) \leq SN_{max}$, all I-frames from SN_{min} to N/R) – 1 are recorded and the transmission window is moved so that SN_{min} = N(R). With the receipt of a negative recording, additionally SN_{max} = N(R) is reset (11). According to the requirements, the following applies for the sequence number N(S):

$$SN_{min} \leq N(S) \leq SN_{min} + n - 1 \tag{5.1}$$

For the request number N(R), the following applies:

$$SN_{min} \leq N\,(R)\ \leq SN_{min} + \mathrm{n} \tag{5.2}$$

From condition (5.1) and (5.2) it follows that for a unique coding of the sequence number module m, the following must apply:

$$m > n \tag{5.3}$$

With the defined module *m*, the maximum window size is therefore:

$$n_{max} = m - 1 \tag{5.4}$$

5.2.2 Selective Repeat (SR) ARQ

With selective repeat (SR) ARQ, the recipient accepts I-frames, which they do not expect as next, and saves them temporarily. Only the missing I-frames will be requested. After their correct reception, the user data of all temporarily saved I-frames will be forwarded to the next higher layer.

With the SR-ARQ, the recipient must also manage a window of the size *n*. In contrast to the transmitter (see section 5.2.1), the recipient only needs a variable *RN*, which describes the lowest not yet correctly received I-frames. The recipient thereby accepts all I-frames, for their sequence number *N(S)*, the following applies:

$$RN \leq N\,(S)\ \leq RN + \mathrm{n} \tag{5.5}$$

Under consideration of the relationships (5.1) and (5.2), the valid sequence number follows the area with the relationship (5.5):

$$RN - n \leq N\,(S)\ \leq RN + n \tag{5.6}$$

For a unique coding of the sequence numbers module *m* must therefore apply:

$$M > 2n - 1 \tag{5.7}$$

With the predefined module *m*, the maximum window size for the SR-ARQ-protocol is:

$$n_{max} = \frac{m}{2} \tag{5.8}$$

5.3 ARQ-Protocols for the real-time-oriented service classes

A minimization of the cell loss ratio (CLR) through ARQ-protocols with a disrupted transmission channel always leads to an increased delay of the information frames due to the transfer repeats. Depending on the service class, two groups of ARQ-protocols are used for the wireless interface:

Standard ARQ-protocols: For the ABR and the UBR service classes, no maximum cell delays are defined. In the LLC layer, conventional HDLC-related ARQ protocols (11) can be used.

Real-time ARQ-protocols: connections of the real-time-oriented CBR and VBR service classes have high requirements for the compliance of a maximum delay T_{dmax}. Thus, the delay of the information frame through the ARQ-protocol is the determining parameter. For these service classes, innovative ARQ-protocols are used on the wireless interface, which adjust the effort for the error correction to the service level requirements of the virtual connection.

For the real-time-oriented service classes, two variations of the newly developed SR / D-ARQ-protocol are investigated, which are based on the SR-ARQ-protocol implemented in chapter 5.2 in their functionality. They are capable of adjusting the effort for the error correction of the service level requirements of the virtual connection. This adaptation is reached for conventional AQR-protocols through the fact that

1. The number of transfer repeats of an ATM-cell is dependent on its scheduler under observation of the service level requirements and the channel load.
2. ATM-cells may be rejected.

The transfer repeats are controlled based on the dates of the ATM-cells through the scheduler (see 4.1) and thus, treated as preferential. The two investigated protocol variations are different in the type and manner as shared with the recipient for the discarding of the ATM-cells (explicit or implicit). The receipt types are summarized in table 5.1.

5.3.1 Discarding ATM-cells

By discarding cells that have exceeded their schedules, short-term overload situations can be avoided or dismounted, the waiting times of the following cells can be shortened and their probability of exceeding the schedule can be lowered. In the following situations, cells can be rejected:

1. Cells, which have not been assigned a sequence number, can be rejected without effect on the ARQ-protocol.
2. By the first transfer, a cell is added to the transmission window and receives a sequence number. The rejection of such a cell is not intended in known ARQ-protocols and through the request for the transfer repeat, it leads the cells rejected by the recipient to deadlocks.

Receipt type	Abbreviation	Description *
Receive Ready	RR(N)	N is the next expected I-frame, I-frames with S < N are positively received. With deterministic frame runtime T_{loop}, the transfer of all I/frames can be requested through a receive ready with S ≥ N, see 5.3.2
Selective Reject	SREJ(N)	Requests the I/frames with the sequence number N for the repeat transfer.
First Selective Reject	FSREJ(N)	Like SREJ(N), all I-frames are positively received with S < N.
Reject	REJ(N)	Requests the transfer repeat of all I-frames with S < N.

*S stands for the sequence number of the I-frames

Table 5.1: Receipt types of the SR/D-ARQ-protocols

3. C
ells, which wait in the recipient for the transfer repeat of a cell with a lower sequence number, before exceeding their schedules, they can be forwarded to the next higher protocol layer. After receipt of the missing cell, these must be rejected in the recipient in order to maintain the sequence of the ATM-cells. For this procedure, the transfer of the schedules from the ATM-cells is required, which has the consequence of a higher signalizing overhead.

In the following, two different procedures are described as to how the deadlocks can be avoided, which arise through the request of transfer repeats according to 2. The first procedure guarantees the compliance of the transfer sequence of the ATM-cells, but causes additional signaling effort. The second procedure works without additional signaling traffic, but permits the exchange of individual cells in the case of an error.

5.3.1.1 Explicit notification of the recipient with discard messages

In order to guarantee the transfer sequence of the ATM-cells after discarding a cell that was already assigned a sequence number, the transmitter will not transfer the discarded cells, but rather instead a short discard message, which only contains a sequence number and is transferred like a receipt. The recipient treats the discard messages like a normal I-frame, this means it must make a receipt of the discard message. Figure 5.2 shows an example of a protocol sequence. The frames I(0) and I(2) are lost during the transfer. The SREJ(2) receipt, with which the repeat request of the I(2) frame is requested, is also lost. Due to the delay through the repeat of the SREJ(2), the ATM-cell of the I(2)-frame will be discarded in the meantime. This is shared with the recipient with the DISCARD(2)-message, which is transported piggyback to the I(5) frame.

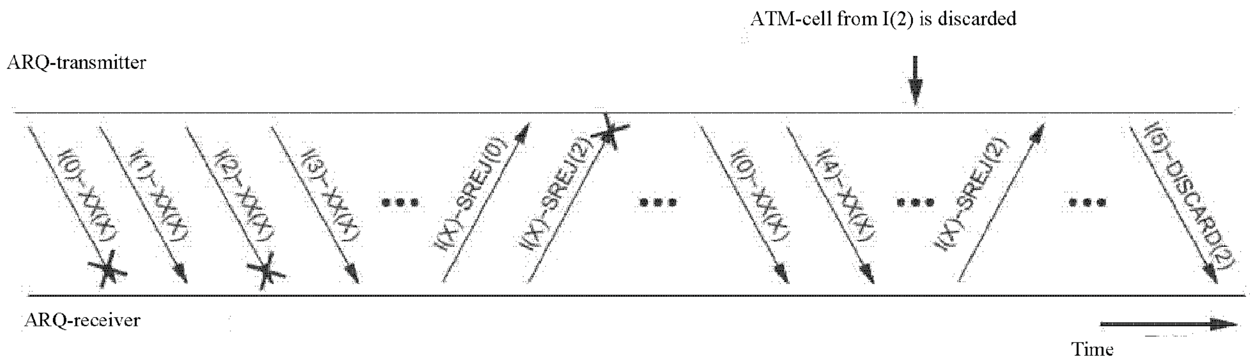


Figure 5.2: Example protocol sequence from the SR/D-ARQ-protocol: discarding of ATM-cells and information from the recipient through discard messages

If the recipient has requested multiple cells that have been discarded, then due to the chronological sequence of the ATM cells, it is sufficient to only share the discarding of the cells through the discard message with the highest sequence number.

Discard messages are in competition with receipts. In order to avoid deadlocks, the punctual transfer of receipts and discards messages must therefore be guaranteed, see the examples in (9).

5.3.1.2 Implicit discarding through moving the window

Cells are discarded in overload situations whereby the channel is then additionally charged through the required discard messages. ATM-cells that have already been assigned a sequence number can also be discarded without the transfer of discard messages by having the transmitter moving their transmission window correspondingly when rejecting cells. Through this, I-frames are delivered, which are outside of the recipient window and which would be invalid by the standard SR-ARQ-protocols. Based on this I-frame, the recipient recognizes that the transmitter has discarded cells, also moves their window and ends the waiting for the I-frame of their sequence numbers outside of the window. Figure 5.3 illustrates an example protocol sequence in which the recipient requests the transfer repeat of the I(1)-frame with a SREJ(1) receipt. The transmitter discarded the frames in the meantime and moved the transmission window. Thus, they sent the I(5) frames, after the receipt of which the recipient cancels the waiting for the I(1) frame and also moves their window.

However, the recipient cannot make a difference between I-frames discarded and incorrectly outside of the reception window so that in the worst cases, there may be a doubling or exchanging of ATM-cells.

With a high frame error ratio, cells can be exchanged if initial transfers are changed with transfer repeats from rejected I-frames. For this, however, two events must meet together: the lack of the oldest cell in the reception window and the non-reception of $x = m - n_{max} = m/2$ (m = module, n_{max} = m/2 = maximum window size) cells following each other due to transfer errors. If the next cell is successfully received, it will incorrectly be held as an I-frame already discarded for a transfer repeat (see figure 5.4).

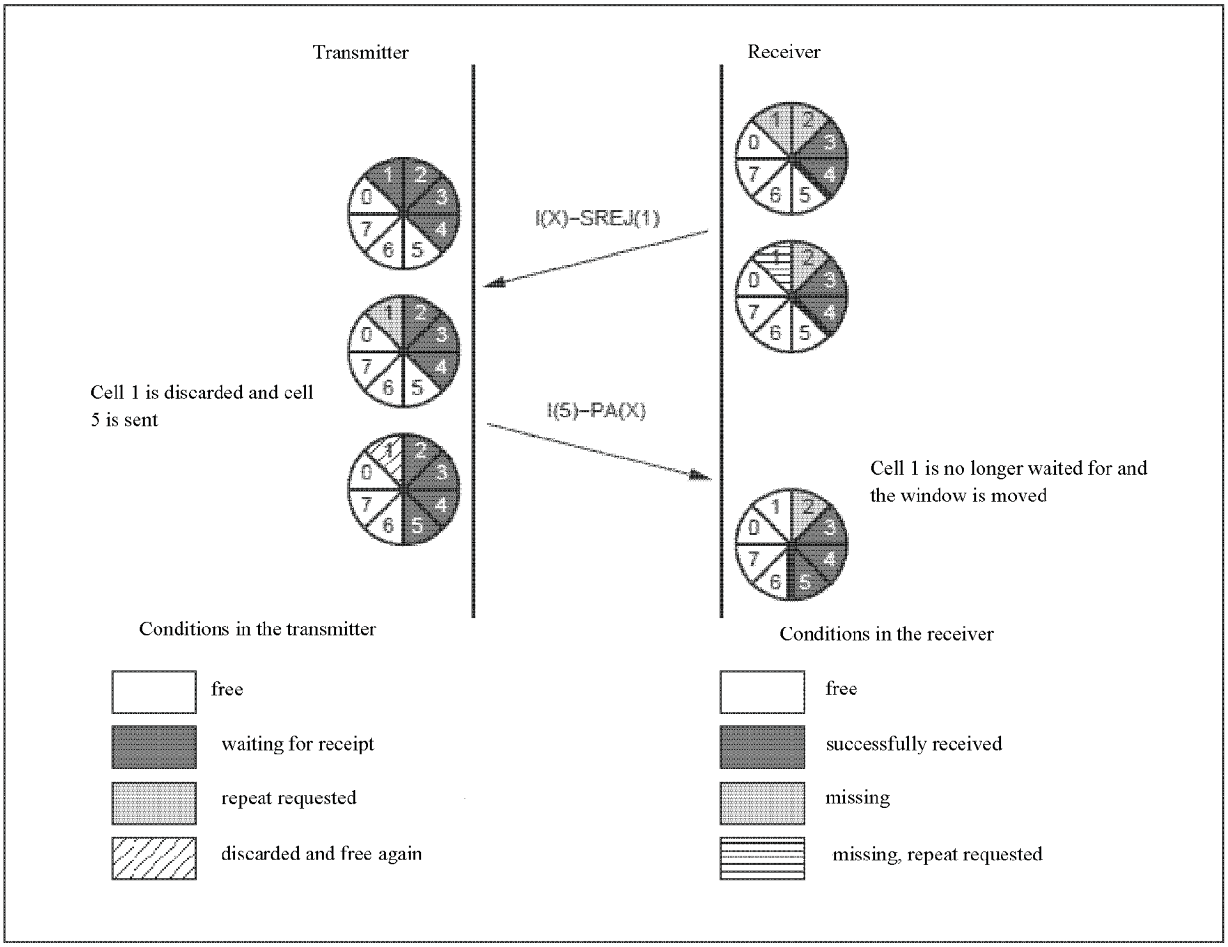


Figure 5.3: Example protocol sequence of the SR / D-ARQ protocol (max. window size $n_{max} = 4$): automatic moving of the window after the discarding of ATM-cells

This is more probable the smaller the ARQ-window (n_{max}) is selected. A detailed observation and a quantification of the probability for the meeting of these events can be found in (36).

5.3.2 Methods for the minimization of transfer delays

In the literature, a row of methods are introduced with which the transfer delays can be minimized by ARQ-protocols (1, 37). As an example, the advantageous exploitation of this knowledge over the duration of ARQ-frames is described.

The cycle delay T_{loop} is defined as the time span between the delivery of an I-frame in the forward direction up to the receipt of a *directly returned* receipt in the opposite direction. With the help of T_{loop}, the transmitter of I-frames can determine the point in time starting at which a received receipt is in regards to this I-frame. The transmitter can recognize the I-frame as lost if after expiration of the cycle delay a receipt is received, but not in regards to this I-frame (with the exception of the SREJ, which is always only in regards to a certain I-frame and does not move the transmitting window). In figure 5.5., this is explained with an example of a protocol sequence. The I(2), I(3) and I(4) frames are lost.

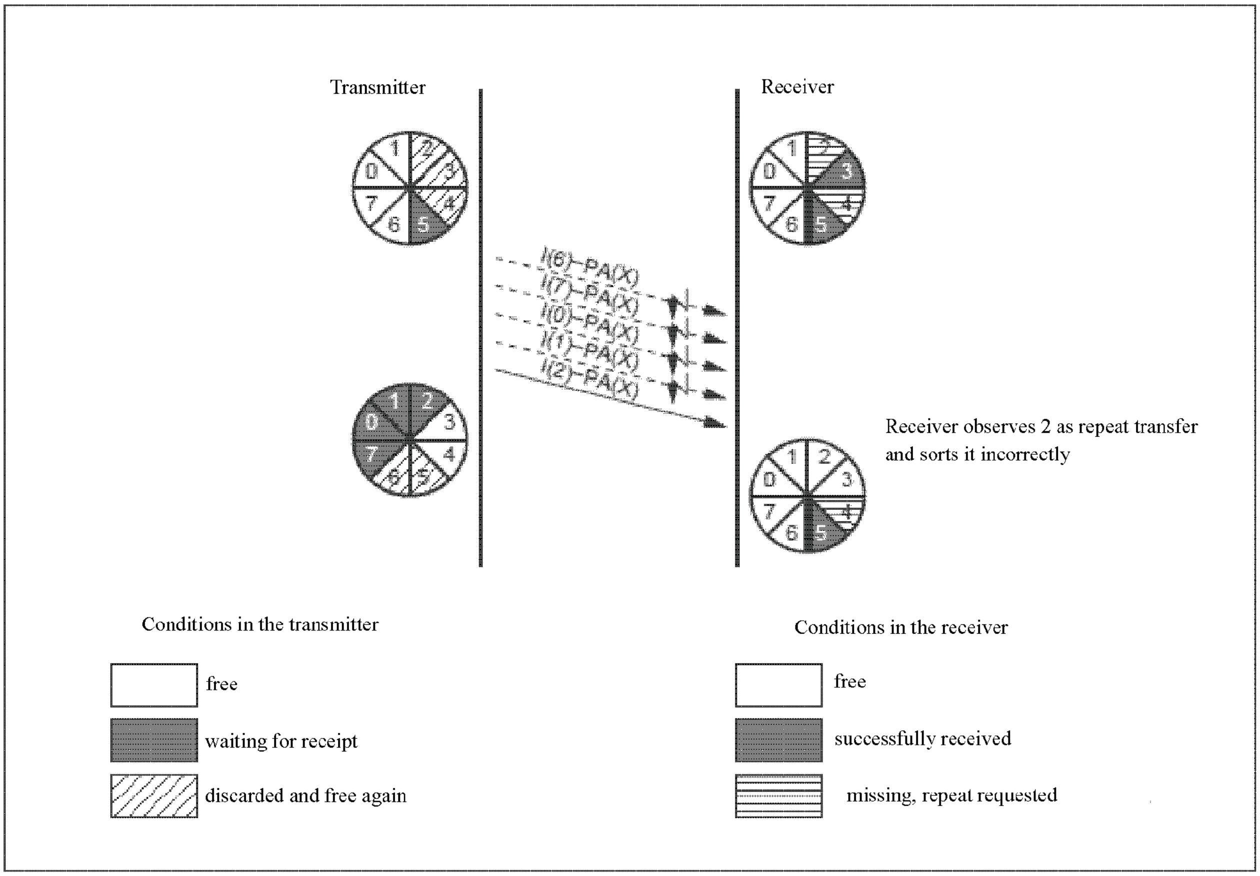


Figure 5.4: Incorrect exchange of ATM-cells in phases with a high frame error ratio

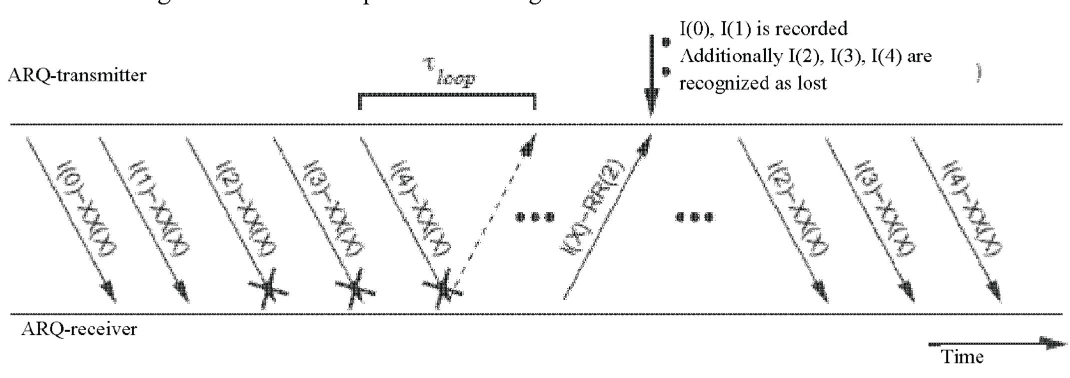


Figure 5.5: An example of a protocol sequence of the SR / D-ARQ-protocol (with running numbers module 16): advantageous exploitation of the known duration of ARQ-frames

Receiver can recognize this first through the receipt of another I-frame with a higher running number, which did not occur until the delivery of the positive receive-ready RR-(2)-receipt. The transmitter knows, however, that the RR(2)-receipt is also in regards to the other I-frames and recognizes these frames as lost.

5.4 No reject receipt with implied discarding

If the procedure of the implied discarding is used, the reject-receipt cannot be used, because it can otherwise lead to deadlocks.

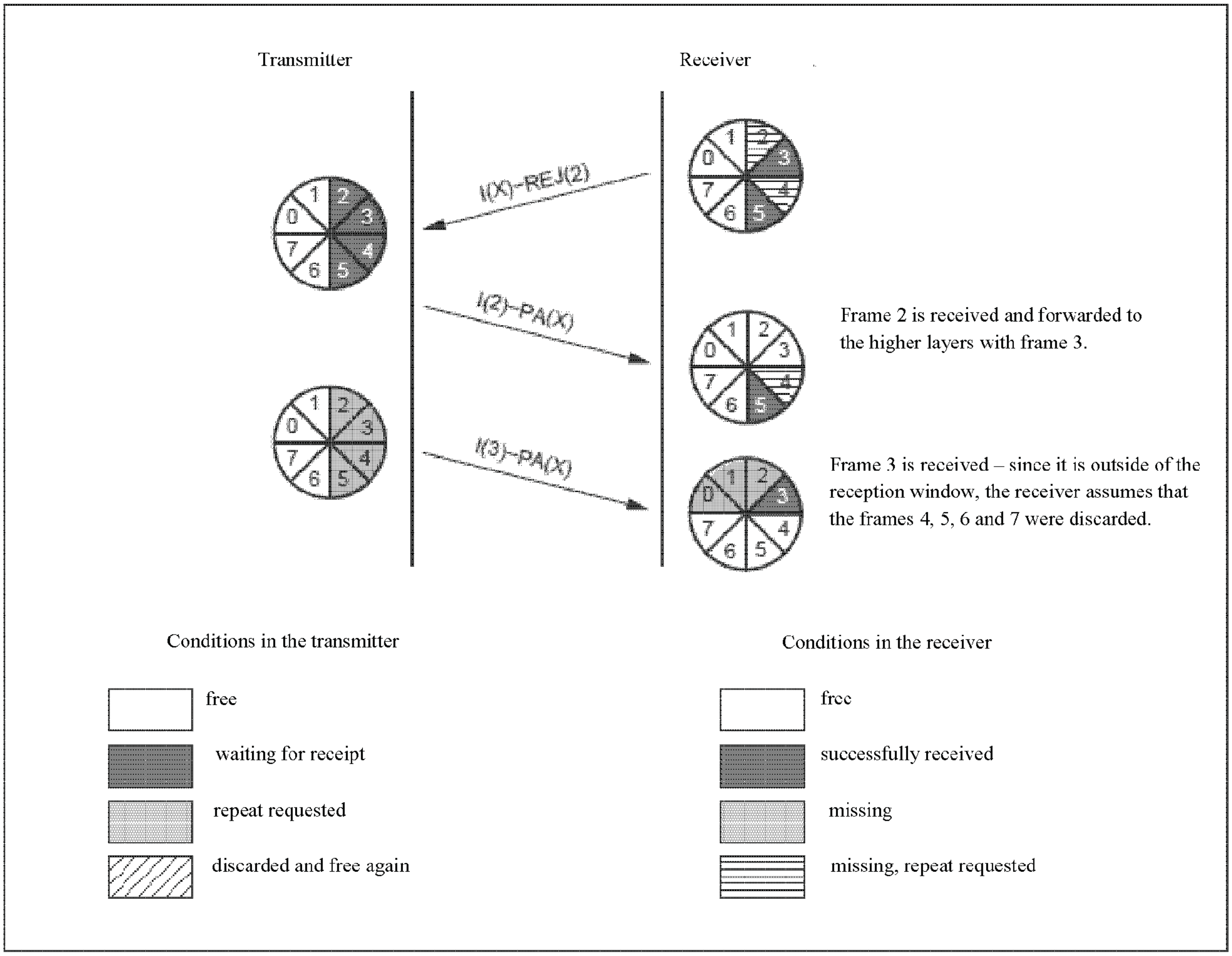


Figure 5.6: Reject-receipt without previous deletion of receipt window

Figure 5.6 shows an example protocol sequence. The receiver has received I(3) and I(5), I(2) and I(4) are lost. Thus, all frames are requested again with REJ(2). I(2) is received and transferred to the higher protocol layers with I(3), which was already received. Due to the REJ(2), the transmitter sends frame I(3) next. This is located outside of the reception window and is interpreted by the receiver so that the frames I(4), I(5), I(6) and I(7) are discarded. This problem also does not occur if the recipient deletes their receipt window before the delivery of an REJ. Here there may also be deadlocks if temporary frames are discarded in the transmitter. An example protocol sequence is shown in figure 5.7. Here the transmitter discarded the frames I(2), I(3) and I(4) before reception and answers to the REJ(2) with I(5), which triggers the renewed delivery of the REJ(2) by the receiver. By the procedure of the implied discarding, the REJ-receipt cannot be used, which with a burst-type traffic and correlated channel error can lead to longer delays, because in this case sequential frames are frequently lost and then must be individually requested with the help of SREJs.

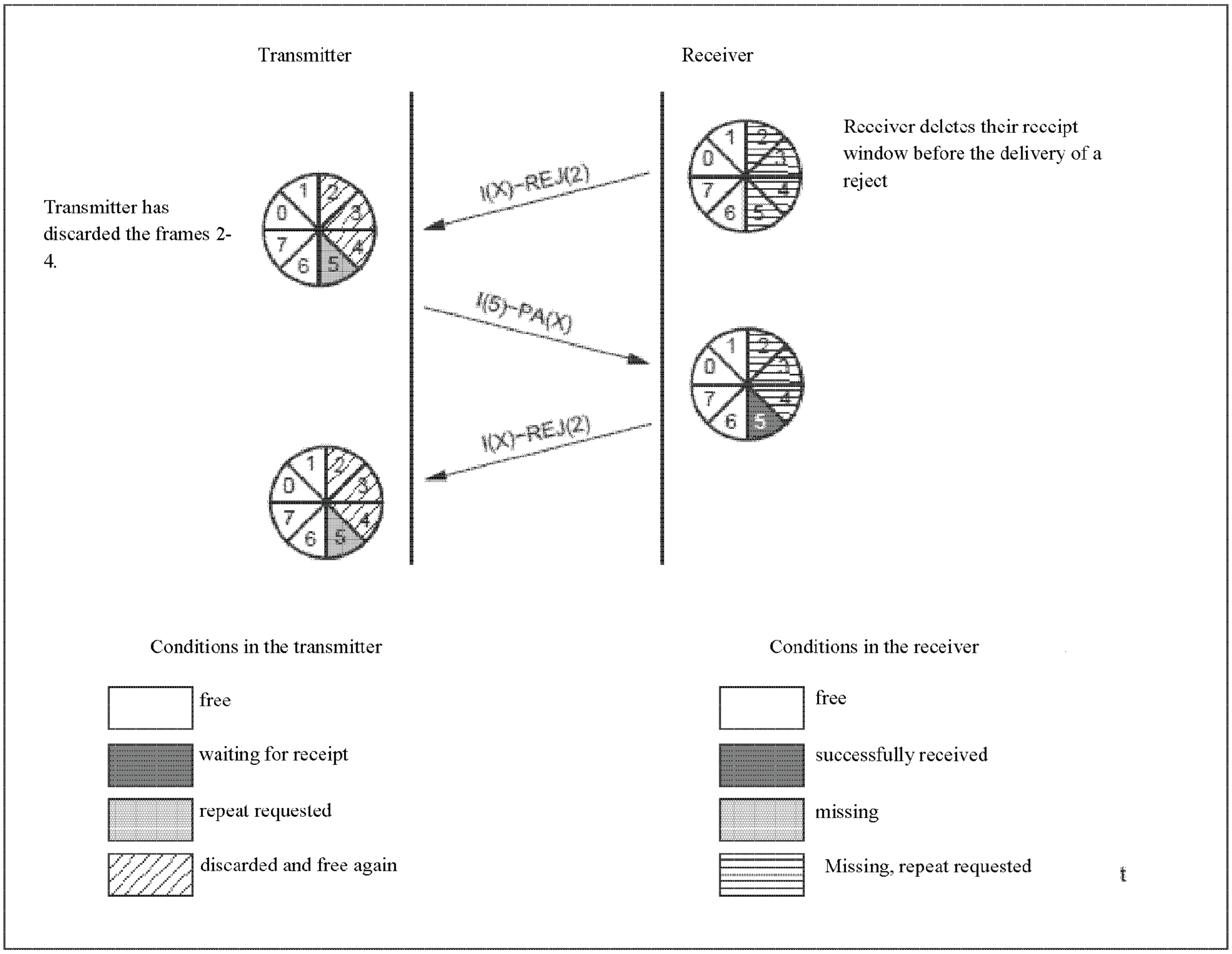


Figure 5.7: Reject receipt with prior deletion of receipt window

5.5 Development of long wait times in the receiver with implied discarding

During the investigation of the procedure for the implied discarding, the problem occurred that cells wait a very long time in the receiver before they can be forwarded to the higher protocol layers if I-frames with lower frame numbers are missing. These long wait times, particularly with low-rated connections, result from the fact that information frames are used in order to inform the receiver about discarded cells. If the waiting line from the transmitter is now empty, so there are no information frames to be delivered, the receiver cannot be informed about discarded cells and always requests the missing I-frames again with the help of SREJs for the transfer repeat, see figure 5.8. The number of cells waiting in the receiver that must be discarded at some time due to the schedule being exceeded must be kept low through a small ARQ-window, nevertheless, the channel is charged through the constant repeat requirements for I-frames with ATM-cells that no longer exist. Furthermore, by small ARQ-windows, the probability for an incorrect sorting of the cells is higher, see section 5.3.1.2.

A procedure must be found to limit this load and to cancel the waiting for the missing I-frames without transferring the date of the ATM-cells, which leads to excessive signaling overhead. Due to these concerns, during the performance evaluation of the protocol plane in this work the

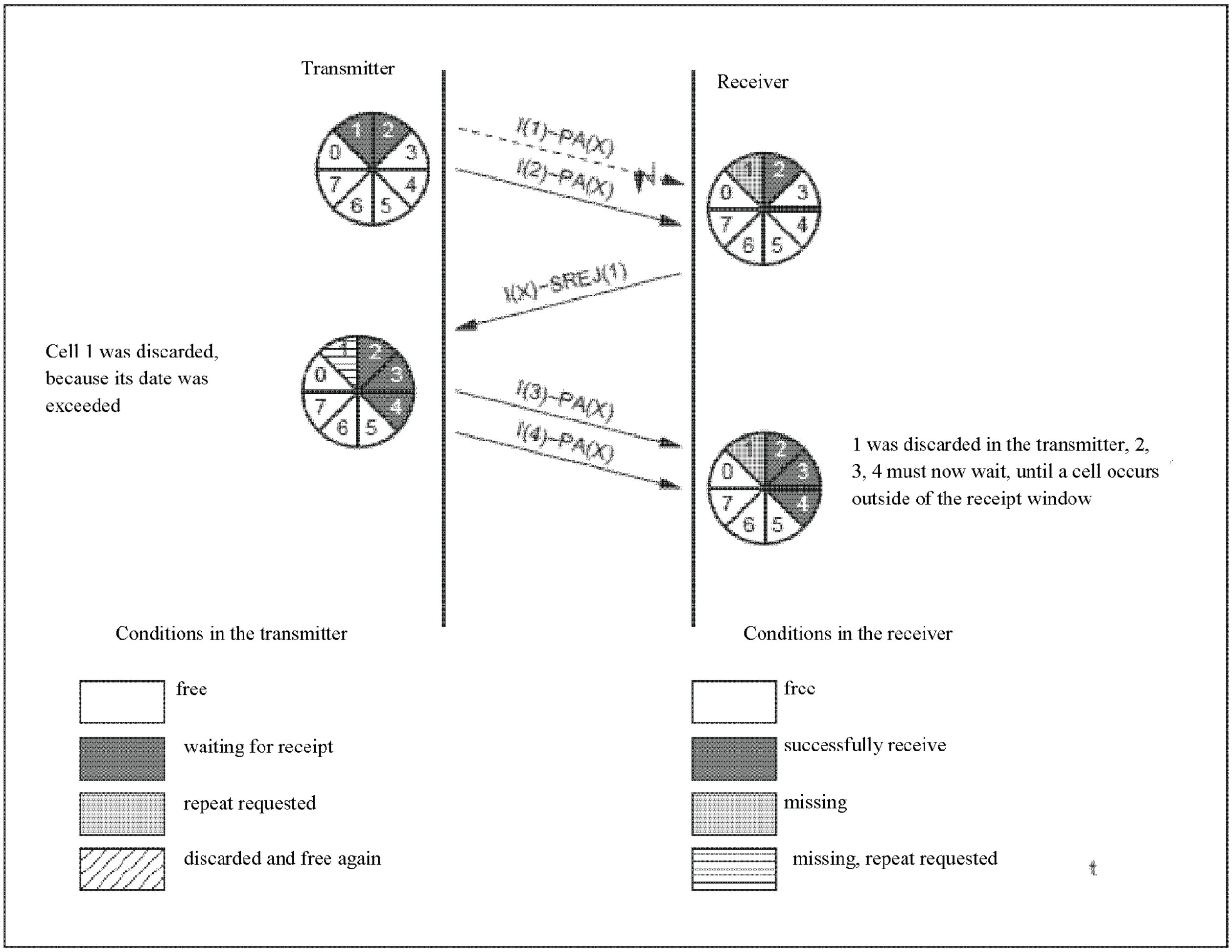


Figure 5.8: Development of long waiting times with implied discarding

SR/D protocol is only used in the variation, which notifies the receiver about discarded cells explicitly with the help of the discard messages.

Receipt Strategies

The transfer of receipts by the usage of ARQ-protocols for connections with real-time requirements is of central importance for the service level. On the one hand, lost or disrupted information frames can be requested through negative receipts and the cell losses of the connection can be controlled, on the other hand the point in time and the number of repeat requests determines the delay of the ATM-cells and therefore has an important influence on the date exceeding ratio of the cells.

The control of the receipt transfer, in addition to the determination of the transfer sequence of the waiting ATM-cells, is a task of the scheduler. Here the reservation decisions and the transfer sequence are determined similarly by the waiting ATM-cells and the receipts. In the following, the procedures implemented and investigated in this work for receipt transfer are introduced, whereby the consideration of the real-time oriented service classes is in the foreground. For the illustration of the algorithms, elements from the specification language SDL are used. Here it deals with overview illustrations and not so much with exact formal specifications.

6.1 The priority of receipts

In the following, a high priority illustrates a high importance, which – as is normal in traffic theory – is expressed through small number values. The decisions from the scheduler in regards to the receipt transfer are based on the priorities of the receipts and the number of waiting ATM-cells from the respective DCH. Here, depending on the observed transfer entities, a difference is made between the following receipt priorities:

1. Priority $P_{Ack\,\mathrm{BS}-\mathrm{R}}(t)$ with which the receiver in the base station would like to deliver a receipt
2. Priority $P_{Ack\,\mathrm{WT}-\mathrm{R}}(t)$ with which the receiver in the terminal would like to deliver a receipt
3. Priority $P_{Ack\,\mathrm{BS}-\mathrm{S}}(t)$ with which the transmitter in the base station would like to receive a receipt

The priority of receipts is based on the schedule of the affiliated ATM-cell. Since this date, however, is not known in the receiver (the information frame normally does not carry the schedule of the cells), the reception time of the information frame and the maximum allowed delay of the virtual connection are used as a basis for all priority calculations. The delay is used in order to consider the connections corresponding with their service level requirements if the receipts from different connections compete with each other in the scheduler.

The parameter t stands for the time dependency of the sizes and describes the current system time ("now").

6.1.1 Priority of positive receipts

For positive receipts (*Receive Ready, RR)*, the priority $P_{RR}(t)$ is determined from the reception point of the oldest not yet received cell T_{rec} and from the maximum delay T_{dmax} of the connection:

$$P_{RR}(t) = T_{rec} + T_{d_{max}} - t \qquad (6.1)$$

6.1.2 Priority of negative receipts

The priority of negative receipts (*First Selective Reject, FSREJ, Selective Reject, SREJ and Reject, REJ*) can only be determined if an information frame is received, which was not expected as the next one. Only then will the recipient note that information frames have been lost. The missing information frames must be requested again with the help of negative receipts. The priority of the individual SREJ-receipt with index I is calculated through an interpolation procedure:

$$P_{SREJ}(t)_i = T_{rec}(n) + i * \frac{T_{rec}(n) - T_{rec}(n-1)}{k+1} + T_{d_{max}} - t \quad i = 1, 2, \ldots \qquad (6.2)$$

Here $T_{rec}(n)$ is the time of receipt of the last received information frame, $T_{rec}(n-1)$ is the time of receipt of the frame before this and k is the number of information frames missing between this. During the connection establishment, the time of receipt for all places of the receipt window will be initialized with the time of the connection establishment. Thus, it is possible for the interpolation to also be executed when frames have already been lost before the reception of the first information frame. If the reject receipt is supported by the ARQ-protocol being used, it will receive the priority based on the interpolated date of the oldest missing ATM-cell.

Figure 6.1 shows this interpolation procedure for a connection whose maximum delay T_{dmax} = 100 timeslots.

6.1.3 Priority of receipts with set poll bit

As investigations in (9) have shown, a considerable improvement of the service level can be obtained through the preferred treatment of receipts with a set poll bit or receipts which reply to the polls of the sending instance by minimizing the schedule exceeding ratio of the connection. The poll bit is set in the used ARQ-protocols if the sending window is closed, the transmitter therefore cannot send any information frames despite an existing channel capacity. Through the closed transmission window, the delay of the ATM-cells waiting in the transmission buffer is increased. Under service level aspects, the transfer request from the corresponding receipt should be quickly reacted to. That is why in the used receipt algorithms, the priority value of receipts with set poll-bit is lowered by T_{dmax}:

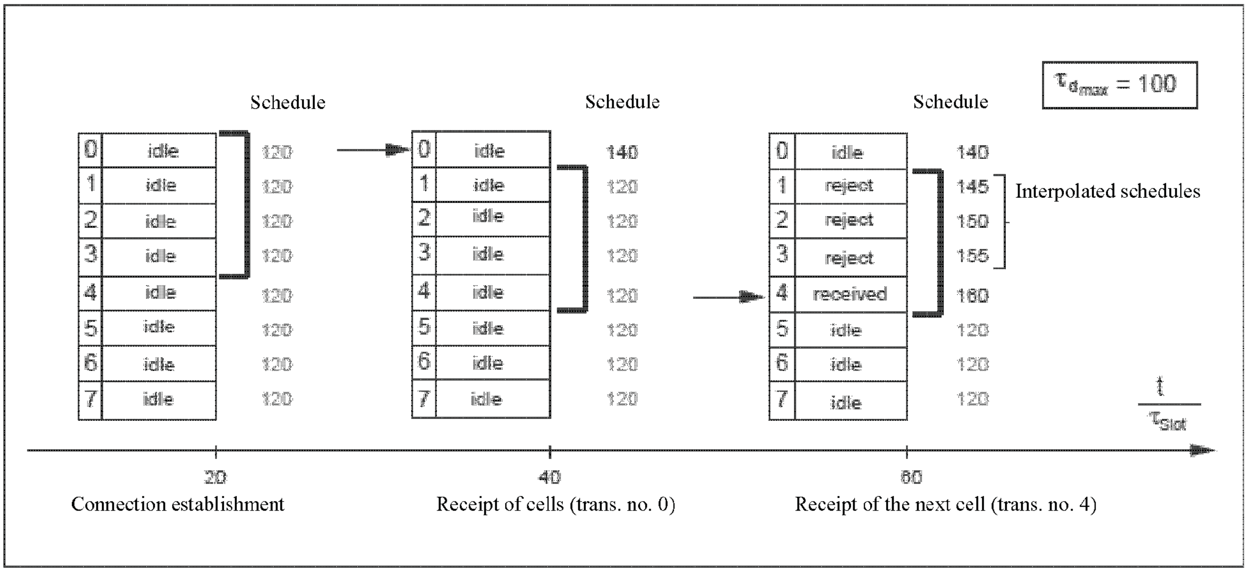


Figure 6.1: Interpolation of the priorities of negative receipts

$$P_{Ack}(t) = P_{Ack}(t) - \tau_{d_{max}} \qquad (6.3)$$

The connection-related parameter of T_{dmax} guarantees the correct ratio of the receipt priorities of the individual connections among each other, which compete with each other in the scheduler during the receipt transfer.

6.1.4 Priority of discard messages

If the discarding of ATM-cells is supported due to the schedule exceeding from the used ARQ-protocols and the partner instances are informed about the discarding through special discard messages (see 5.3.1.1), the discard messages must also be treated preferentially in order to inform the recipient as quickly as possible about the discarded cells so that they can deliver possible waiting, not yet expired cells. For this reason, the discard message is treated just like receipts, which have set the poll bit or answered to a poll, this means the priority of the discard messages is also increased in accordance with comparison 6.3, whereby $P_{Ack}(t)$ is determined for the discard message from the schedule of the oldest discarded ATM-cell in the transmission instance.

6.2 Investigated procedure for receipt transfer

The task of the investigated receipt algorithms is to determine the most important receipt at any time under service level aspects and to select one of the possible procedures for the receipt transfer so that the receipt transfer takes up as little channel capacity as possible. The following procedures were implemented and are available to the scheduler for the receipt transfer:

1. **Piggyback to an ATM-cell in long timeslots:**

In every long timeslot, an LLC receipt can be transferred piggyback style to the up and downlink.

2. **In long timeslots with empty information field (monitoring frame):**
   An individual LLC-receipt is transferred in a long timeslot to an up or downlink, the information field of the frame remains empty. In order to save channel capacity, this possibility should only be used in rare cases.
3. **In combination with other receipts as a bundle receipt:**
   Here multiple (up to 24) LLC receipts are transferred combined in a long timeslot.
4. **In the Period-Ctrl-PDU (only to the downlink):**
   The Period-Ctrl-PDU offers space for up to 6 LLC receipts, which are delivered to the downlink as a broadcast.
5. **In dedicated short poll timeslots (only to the uplink):**
   These timeslots of the RQCH are inserted by the base station in order to request a receipt from a terminal.
6. **In the short timeslots for the random access (only to the uplink):**
   If a terminal must delivery an urgent receipt, it can transfer this in the random access through the RQCH. Due to possible collisions, the delay caused by this until these collisions and the notification of the other accessing terminals, this procedure should be used as little as possible.

In order to select one of these procedures in the scheduler, the group of receipt priorities and the number of waiting PDUs are taken from every single DCH.

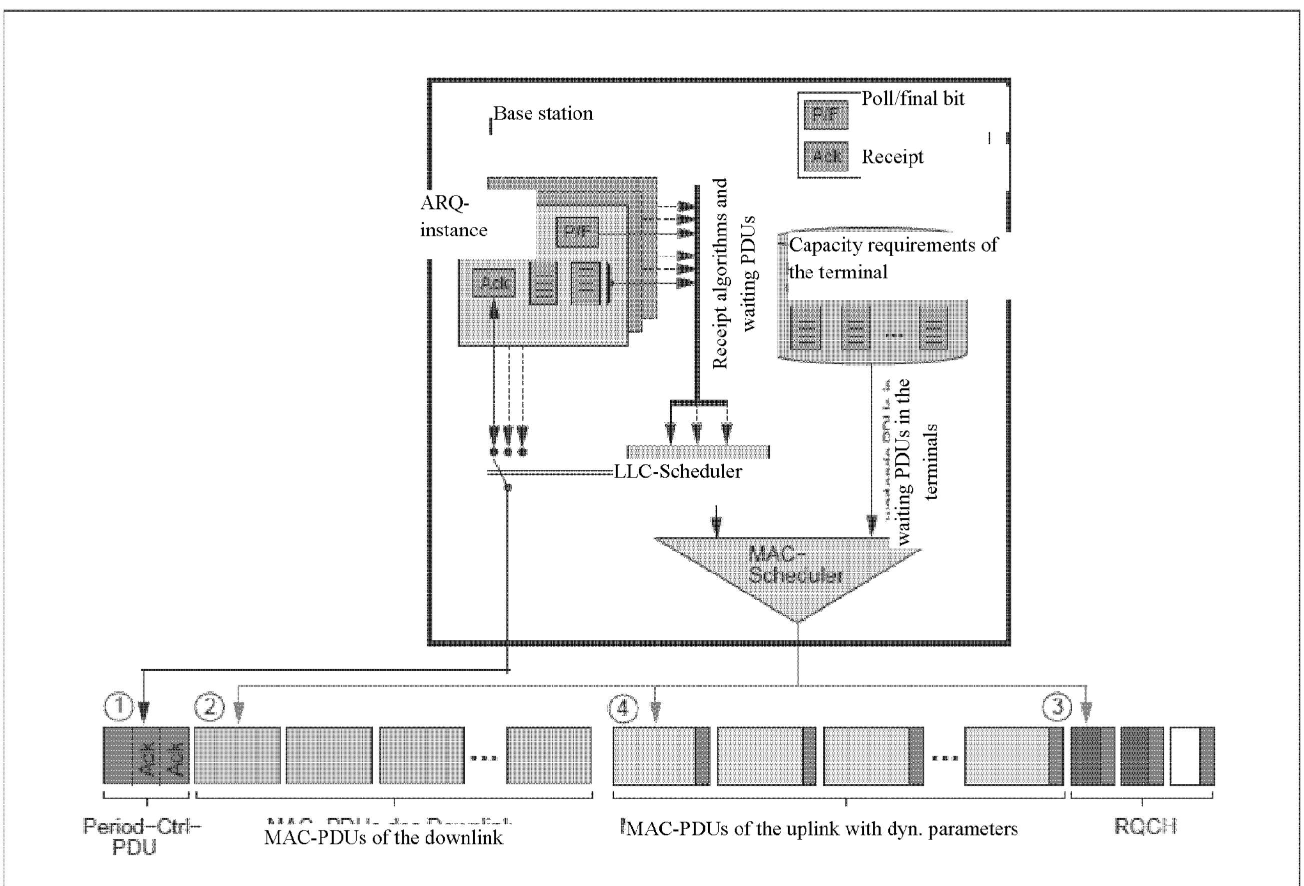


Figure 6.2: Reservation decisions based on receipt transfers

6.2.1 Reservation decisions based on receipt transfers

Figure 6.2 shows the decisions that the scheduler can make during the reservation phase by which channel capacity is reserved based on receipt transfers.

LLC-receipts in the Period-Ctrl-PDU (figure 6.2 (1))

Initially, the receipts are selected that are transferred in the Period-Ctrl-PDU to the downlink in the multi-address mode. The Period-Ctrl-PDU can record up to 6 receipts. The LLC-scheduler determines in a first phase the receipts with the highest priority $P_{Ack_{BS-R}}(t)$ for the DCHs, which do not have to transfer any PDUs. If the capacity for the receipt transfer in the Period-Ctrl-PDU has not yet been exploited, the spaces will be filled with the receipts of the remaining DCHs, whereby the DCHs are queried here in the round-robin procedure and every DCH delivers a positive receipt or so many negative receipts within the scope of the available capacity as it has to deliver. During the composition of the next Period-Ctrl-PDU, the urgent receipts for filling with the DCH will be begun if they were no longer considered during the last time in order to provide for an equal distribution of the available capacity under the DCHs.

Reservation of long downlink timeslots (figure 6.2 (2))

Urgent receipts for DCHs to be sent to the downlink, which also must send PDUs, lead to reservations of long timeslots. Here the principle applies that an important receipt increases the priority of ATM-cells. Long timeslots are also reserved if urgent receipts are to be delivered for DCHs to the downlink, but no ATM-cells from this DCH are waiting and the capacity of the Period-Ctrl-PDU is already exploited for the receipt transfer.

Reservation of dedicated poll timeslots (figure 6.2 (3))

Based on the priorities $P_{Ack_{BS-S}}(t)$ with which the transmitter expects a positive receipt in the base station, it is determined for which DCHs short poll timeslots are added into the signaling period in order to receive a receipt from the partner entity. While by the receipt transfer in the Period-Ctrl-PDU the ARQ-instance with the most urgent receipt can be selected by the LLC-Scheduler, only a short timeslot is reserved for the DCH. Which receipt is transferred is determined by the LLC-scheduler in the terminal and a receipt of the ARQ-instance is not necessarily transferred, whose transmitter triggered the reservation of the short timeslot in the base station.

These short timeslots are only used if within the scope of the known capacity requirements of the terminal, no ATM-cells have to be transferred for this DCH to the uplink. If the terminal has waiting ATM-cells, instead a long uplink timeslot will be reserved in order to receive the receipt in a piggyback manner. Here an urgent receipt also increases the priority of a waiting ATM-cell from this DCH.

Reservation of long uplink timeslots (figure 6.2(4))

If the conditions for inserting a short poll timeslot of multiple ARQ-instances of a DCH within a signaling period are fulfilled, the poll timeslots will be summarized for a long timeslot in which a bundle receipt can then be transferred. Since there are no explicit capacity requirements for receipts through the terminals (see section 6.2.2), no long timeslots can be reserved in the terminals based on the receipt priorities of the receiver.

6.2.2 Capacity requirements of the terminal for receipt transfer

Before the receipt transfers are dealt with in detail, the capacity requirement of the terminals is observed in the following again in regards to the receipt transfer. Capacity requirements for the receipt transfer are only executed in cases of exception, because a receipt is transferred together with the dynamic parameters for the capacity requirement anyway (figure 6.3 (6)). Thus, only the cases are to be observed in which a terminal must transfer more than one urgent receipt. This is the case if multiple information frames are lost and their transfer repeat must be requested. In the investigated receipt algorithms, a long timeslot is requested for a bundle receipt. If no bundle receipts are used, the dynamic parameters that were delivered with the previous receipt receive the most urgent interpolated schedule for the missing cells. The number of waiting cells is set to zero in the dynamic parameters in order to signalize that only a receipt should be transferred.

6.2.3 Influence of the receipt transfers on the transfer phase

During the transfer phase, the LLC-scheduler in the base station and terminals determines which receipts are transferred in the correspondingly reserved timeslots based on the priority $P_{Ack_{BS-R}}(t)$for the base station or $P_{Ack_{WT-R}}(t)$ for the terminals.

Piggyback transfer of receipts (figure 6.3 (1))

If an ATM-cell is transferred during the reserved timeslots, a receipt will be added in every case. This procedure is offered, because the overhead of the physical layer is lowered for the receipt transfer in this way.

Receipt transfer in the monitoring frames (figure 6.3(2))

If only an urgent receipt has to be transferred, this will be delivered in a monitoring frame, this means the usage data field remains empty. This case occurs rarely in the investigated receipt strategies, because the reserved timeslot for transfer of a batch receipt is used in the case of multiple parallel ARQ-instances or multiple negative receipts.

Bundle receipts in long timeslots (figure 6.3 (3))

If multiple urgent negative receipts (SREJ) must be delivered, a long timeslot that was either reserved for the transfer of an ATM-cell or specifically requested for this, will be used for the transfer of a bundle receipt. If the DCH has multiple parallel ARQ-instances, in addition to the instance that triggered the delivery of the bundle receipt, the other instances will be queried within the scope of the available capacities and their (positive and negative) receipts will be transferred.

Receipt transfer in short poll timeslots (figure 6.3(4))

If the terminal was assigned a dedicated short poll timeslot, the LLC-scheduler determines the most urgent receipt for the transfer in this timeslot. At this point, the principle of static priorities between service classes must be deviated from. The real-time oriented service classes must be in direct competition with each other, because the short poll timeslot cannot be assigned explicitly one ARQ-instance. If the static priorities are maintained here, it may be the case that instead of the expected important VBR-receipt, a less important receipt of the CBR-service class is transferred.

Receipt transfer in random access (figure 6.3 (5))

If an ARQ-instance in the terminal must deliver an urgent receipt and there is no other possibility, this receipt can also be transferred through the RQCH in the random access. Here the used receipt algorithms can only deal with a negative receipt, because for urgently needed positive receipts from the terminal, short poll timeslots are inserted for the receipt transfer through the scheduler of the base station in the signaling period.

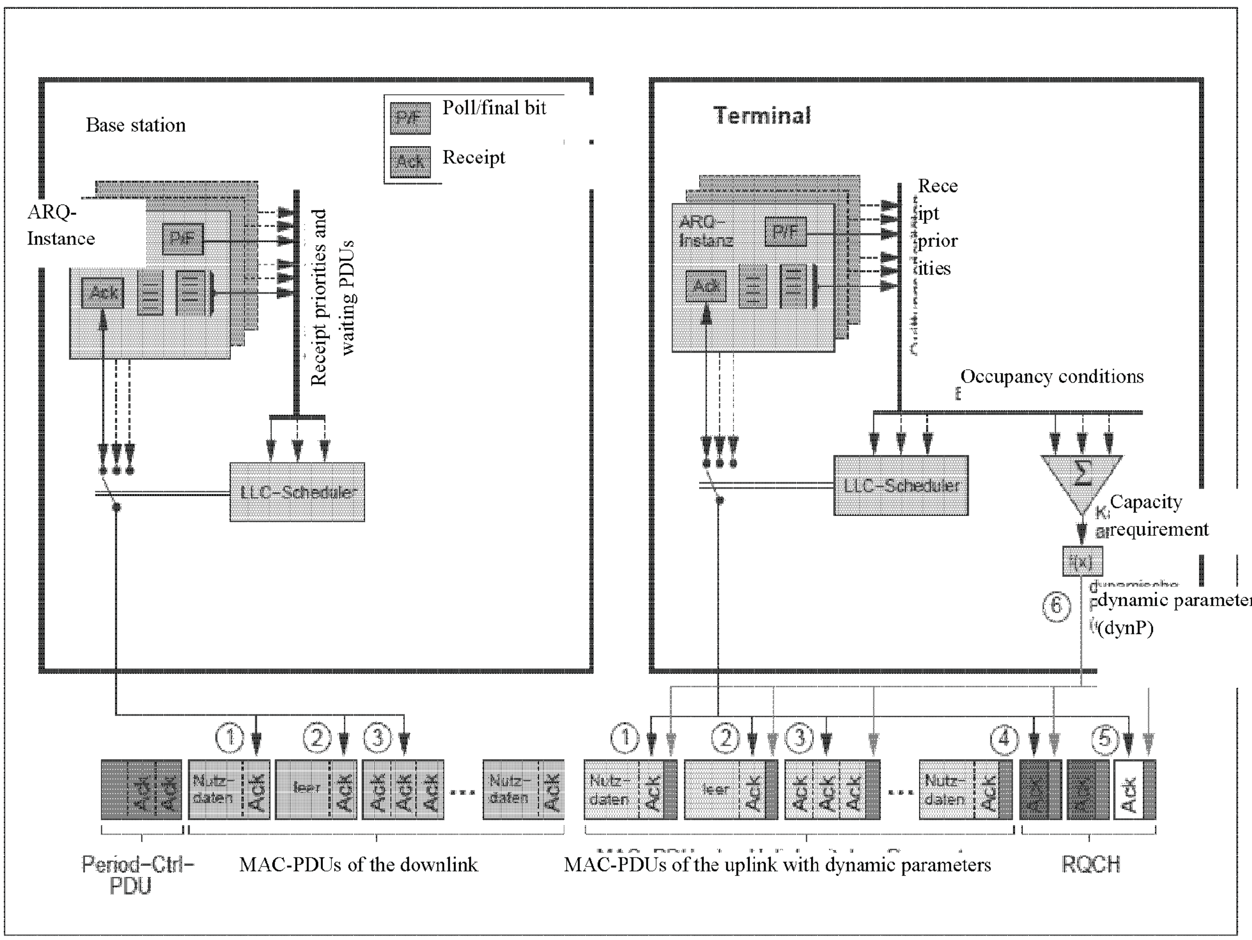


Figure 6.3: Receipt transfer in the transfer phase

6.3 The receipt algorithm of the reservation phase

Figure 6.4 shows a schematic SDL-illustration of the algorithm used for the reservation decisions of the MAC-scheduler. In figure 6.5, the reservation process of the MAC-instance is illustrated with which the scheduling process communicates. In table 6.1, the used variables and parameters are summarized.

Parameter	Label in figure 6.4	Description
$P_{max}(t)$	highest_p	Currently highest priority
$P_{PDU_{BS}}(t)$	P(LocalPDU)	Priority of the most important ATM-cell to be sent in the BS
$P_{PDU_{WT}}(t)$	P(RemotePDU)	Priority of the most important ATM-cells from the terminal to be delivered
$P_{Ack_{BS-S}}(t)$	P(ExpectedAck)	Priority with which a receipt is expected in BS
$P_{Ack_{WT-S}}(t)$	P(LocalAck)	Priority of the most important receipt to be sent in the BS
$N_{Res\,max}$	max_no_res	Maximum number of reservations
N_{Res}	no_res	Current number of reservations
$N_{Poll\,DCH}$	no_p_dch	Number of poll timeslots per DCH
$N_{Ack-PCTRL\,max}$	max_no_pctrl	Maximum number of receipts in the Period-Ctrl-PDU
$N_{Ack-PCTRL}$	no_pctrl	Current number of receipts in the Period-Ctrl-PDU
N_{local}	loc_pdu	Number of waiting PDUs from the BS
N_{remote}	rem_pdu	Number of waiting PDUs in the terminal
$P_{T\,poll}$	T_Poll	Priority threshold for short poll timeslots

Table 6.1: Parameter of the receipt algorithm in the MAC-scheduler

At the beginning of every reservation phase, the MAC-scheduler receives the number of maximum possible reservations together with the start signal Start_Reservation (max_no_rest) in this signaling period $N_{Res\,max}$. This size is determined through the used MAC-protocol and must not be constantly. After the initialization of the number of poll timeslots per DCH, the current highest priority from the group determines the priority parameter being used [1]:

$$P_{max}(t) = \min\left\{P_{PDU_{BS}}(t), P_{PDU_{WT}}(t), P_{Ack_{BS-S}}(t), P_{Ack_{WT-S}}(t)\right\} \tag{6.4}$$

Depending on which priority has been used by this minimum formation, the algorithm changes:

[1]Here the min-function is used, because small number values stand for high priorities.

1. If the priority with which a transmitter in the base station expects a (positive) receipt is at highest

$$P_{max}(t) = P_{Ack_{BS-S}}(t), \tag{6.5}$$

the database will be queried for the capacity requirements in order to determine the number N_{remote} of the waiting ATM-cells in the terminal of this DCH.
If

$$N_{remote} \neq 0 \tag{6.6}$$

applies, a long uplink timeslot is reserved and the priority of a waiting ATM-cell is increased by the receipt. Otherwise, it is checked to see if this receipt has exceeded a priority threshold

$$P_{Ack_{BS-S}}(t) < P_{T_{poll}} \tag{6.7}$$

and, if applicable, a short poll timeslot is reserved in order to receive the receipt from the terminal. If a short poll timeslot has been reserved for this DCH in this signaling period, this reservation will be transferred into the reservation of a long uplink timeslot.

2. If the transfer of an ATM-cell to the uplink is currently the most urgent

$$P_{max}(t) = P_{PDU_{WT-S}}(t), \tag{6.8}$$

the reservation of a long timeslot occurs for the uplink.

3. If the delivery of a receipt to the downlink has the highest priority

$$P_{max}(t) = P_{Ack_{WT-S}}(t), \tag{6.9}$$

initially the number N_{local} of the waiting ATM-cells of this DCH will be determined for the transfer to the downlink. If

$$N_{local} \neq 0 \tag{6.10}$$

applies, the reservation of a long downlink timeslot results from this. Here the priority of the ATM-cells is increased through the important receipt as well. Otherwise, for this DCH only one receipt is to be transferred to the downlink and the algorithm tries to send this receipt in the Period-Ctrl-PDU. If

$$N_{Ack-PCTRL} < N_{Ack-PCTRL_{max}} \tag{6.11}$$

applies, this receipt can be transferred together with their MAC-Id in the Period-Ctrl-PDU. After this, $N_{Ack-PCTRL}$ is increased by one. If the condition (6.11) is not filled, a long timeslot of the downlink must be reserved, which then only has this one receipt under circumstances. Normally, this timeslot is then used during the transfer phase for a bundle receipt.

4. For the case that the transfer of an ATM-cell to the downlink is of the highest urgency, thus

$$P_{max}(t) = P_{PDU_{BS}}(t) \tag{6.12}$$

applies, the scheduler reserves a long timeslot for the downlink.

Through the use of the schedule function, this reservation requirement is marked as complete and the next important is provided. The algorithm is executed until the number of available reservations in this signaling period is exploited. This is shared with the reservation process of the MAC-instance (figure 6.5) through the signal End_Reservation.

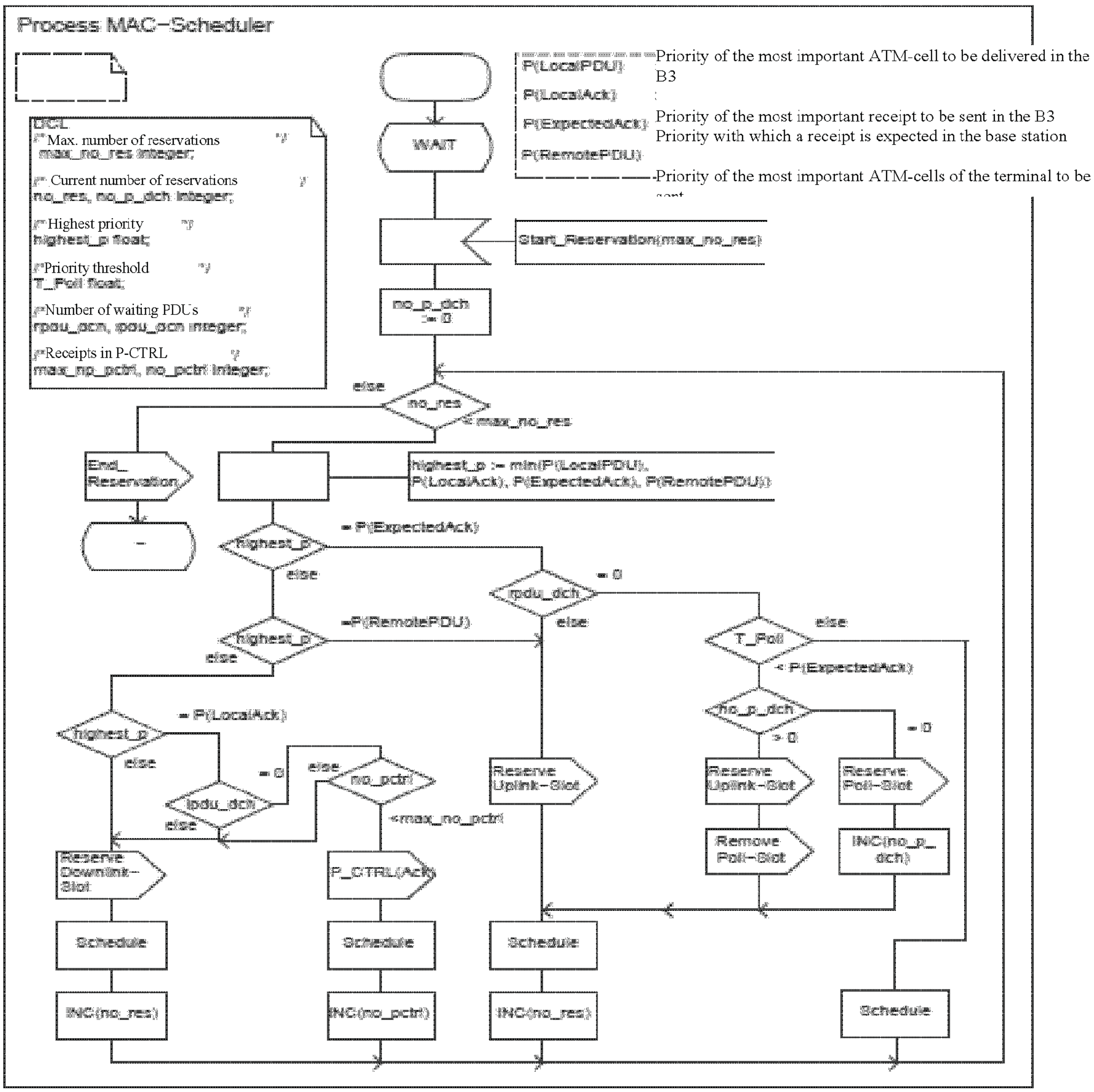


Figure 6.4: SDL-illustration of the receipt algorithm in the MAC-scheduler

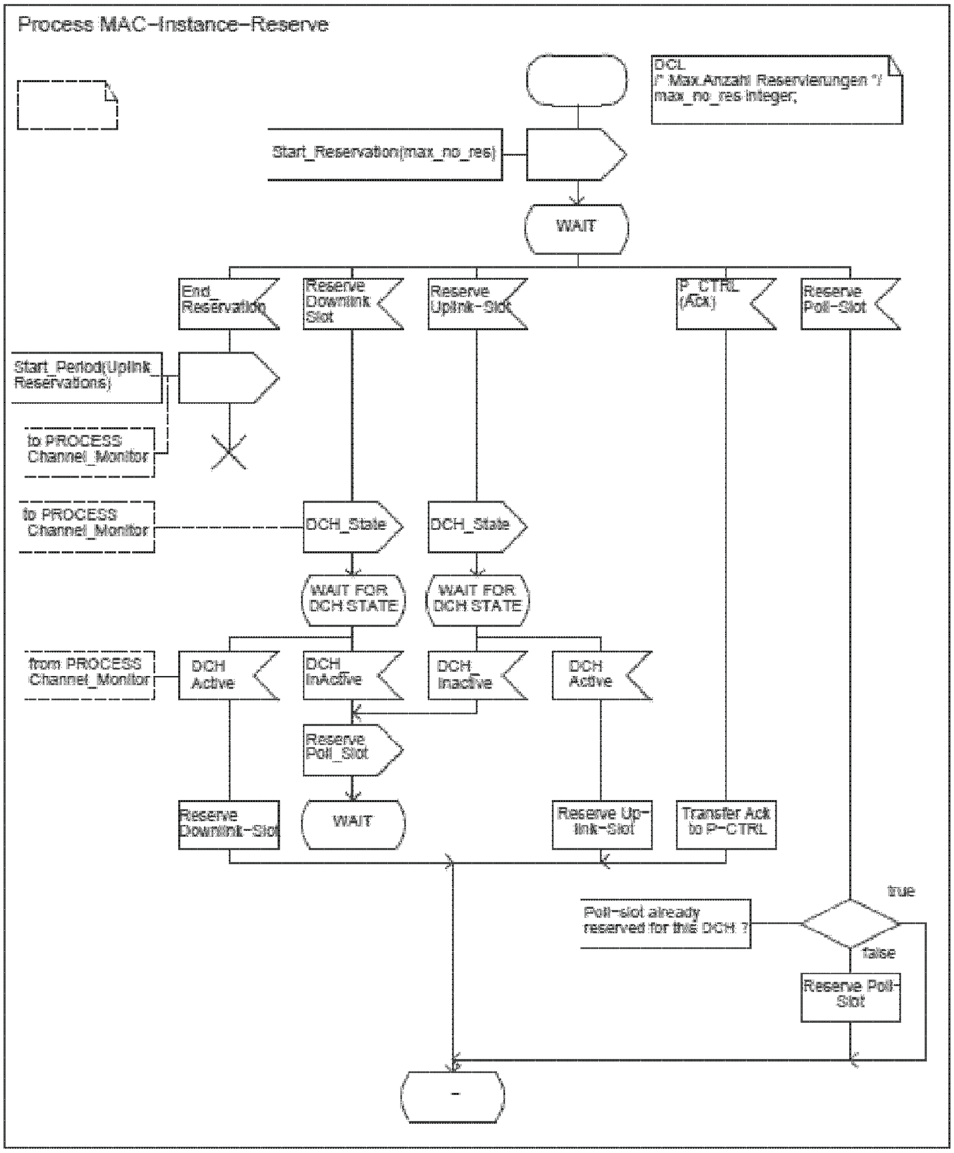


Figure 6.5: SDL-illustration of the reservation process of the MAC-instance with the functions of the channel monitoring

Parameter	Label in figure 6.6	Description
$P_{Ackmax}(t)$	P(Ack)	Highest current receipt priority
$N_{Bundlemax}$	max_no_ack	Maximum number of receipts in a bundle receipt
N_{Ack}	no_ack	Current number of receipts in the service data unit
$N_{ARQ-Ack}$	no_acks (figure 6.8)	Number of receipts from an ARQ-instance to be sent
P_{TRACH}	T_RACH	Priority threshold for the receipt transfer in the random access
T_{Bundle}	T_Bundle	Threshold for the transfer of a bundle receipt in a long timeslot

Table 6.2: Parameter of the receipt algorithm in the TCH-handler

6.4 The receipt algorithm of the transfer phase

While the receipt algorithm of the reservation phase determines which timeslots are reserved due to receipt transfers and which receipts are transferred in the Period-Ctrl PDU, the algorithm of the transfer phase described in the following decides which receipts are transferred in the reserved time slots. This algorithm runs in the so-called TCH-handler object, which contains the corresponding service access points of the MAC-layer and has two designs depending on if this object is in the base station or in the terminal. Table 6.2 shows the variables and parameters being used.

During the transfer phase, for every timeslot the TCH-handler-object receives a request to compose a service data unit (DU) (Signal Transmission_indicator(slot_type)). This signal additionally shares the type of timeslot in which it should now be sent and this determines which elements may contain the service data unit (see figure 4.12):

1. If it should be sent in a long timeslot, the algorithm initially decides if a bundle receipt should be delivered (call of the procedure *Send-Bundle Ack* see section 6.4.1 and figure 6.8). If this is not the case, the most important ATM-cell of this DCH will be requested through the interface of the LLC-scheduler (see figure 6.7) (GetPDU(DCH)) and after receipt (Ind(PDU)) transfers the service data unit (SDU(PDU)). After this, the most important receipt (GetAckPDU(DCH)) will be queried and also transferred to the SDU for the piggyback transfer. If it deals with a long timeslot of the uplink, the service data unit is still amended by the dynamic parameters, see section 4.2.2 (not illustrated in figure 6.6 due to reasons of clarity).
2. If it deals with a dedicated short poll timeslot from the uplink, no ATM-cell will be sent, but rather only the most important acknowledgement from the DCH together with the dynamic parameters.

3. With the short timeslots for the random access (only uplink), the algorithm checks the urgency of the acknowledgement in order to keep the load of the random access channel as low as possible. If the acknowledgement priority does not meet a certain threshold,

$$P_{Ack\,max}(t) < P_{T\,RACH} \tag{6.13}$$

is sent in the optional access and the acknowledgement is transferred together with the dynamic parameters.

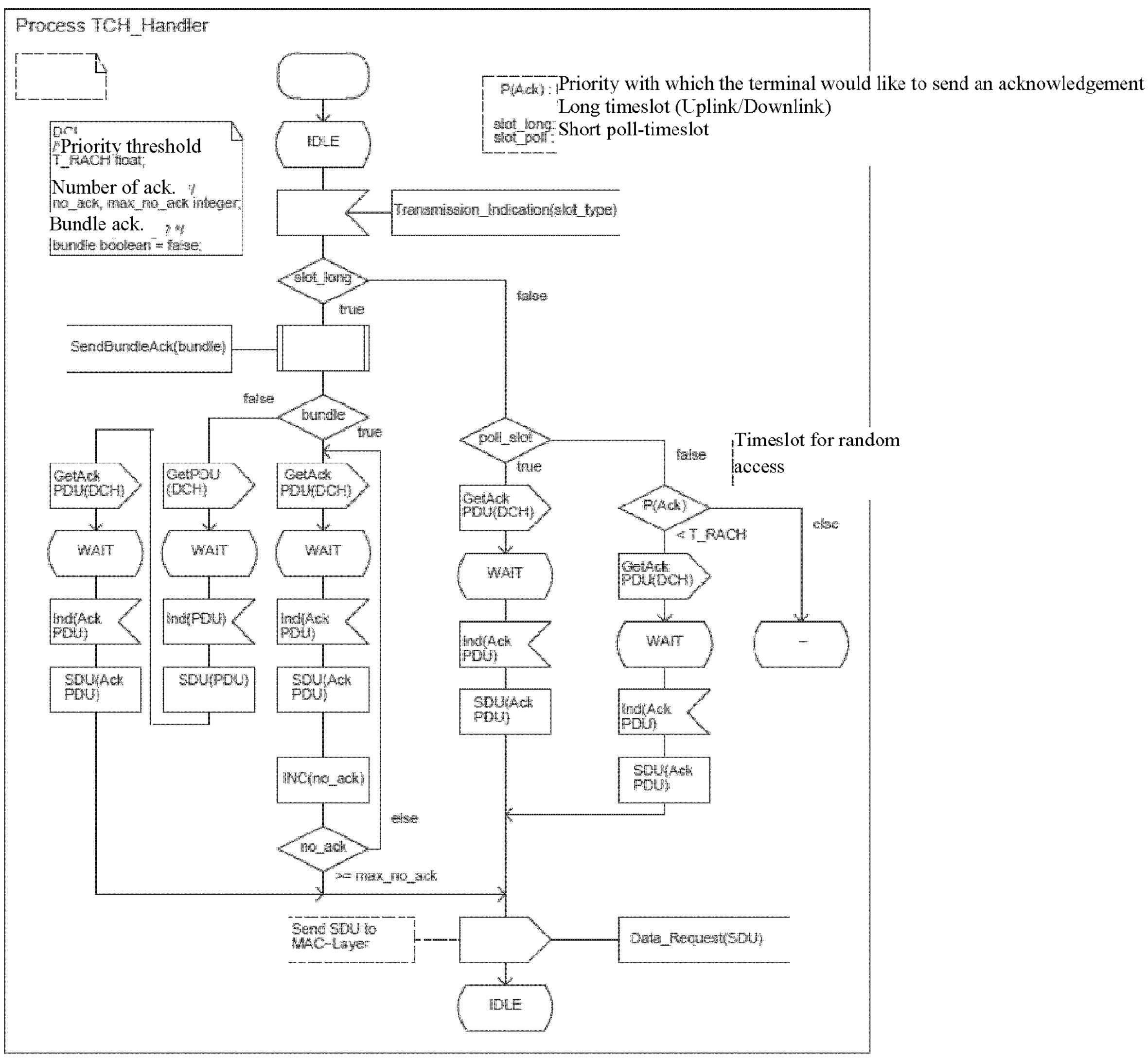


Figure 6.6: SDL-illustration of the acknowledgement transfer in the transfer phase

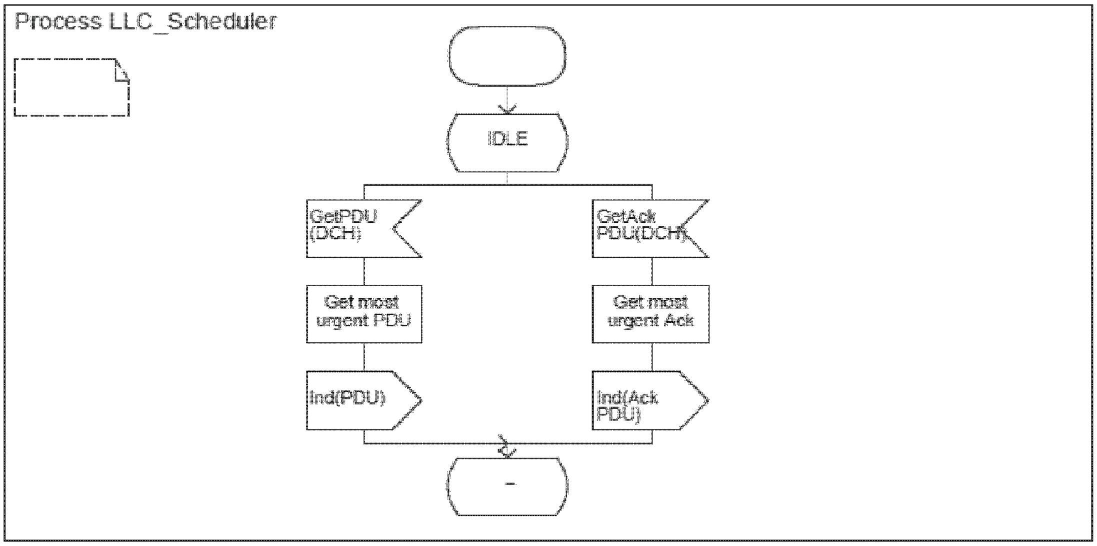


Figure 6.7: SDL-illustration of the interface of the LLC-scheduler for the TCH-handler

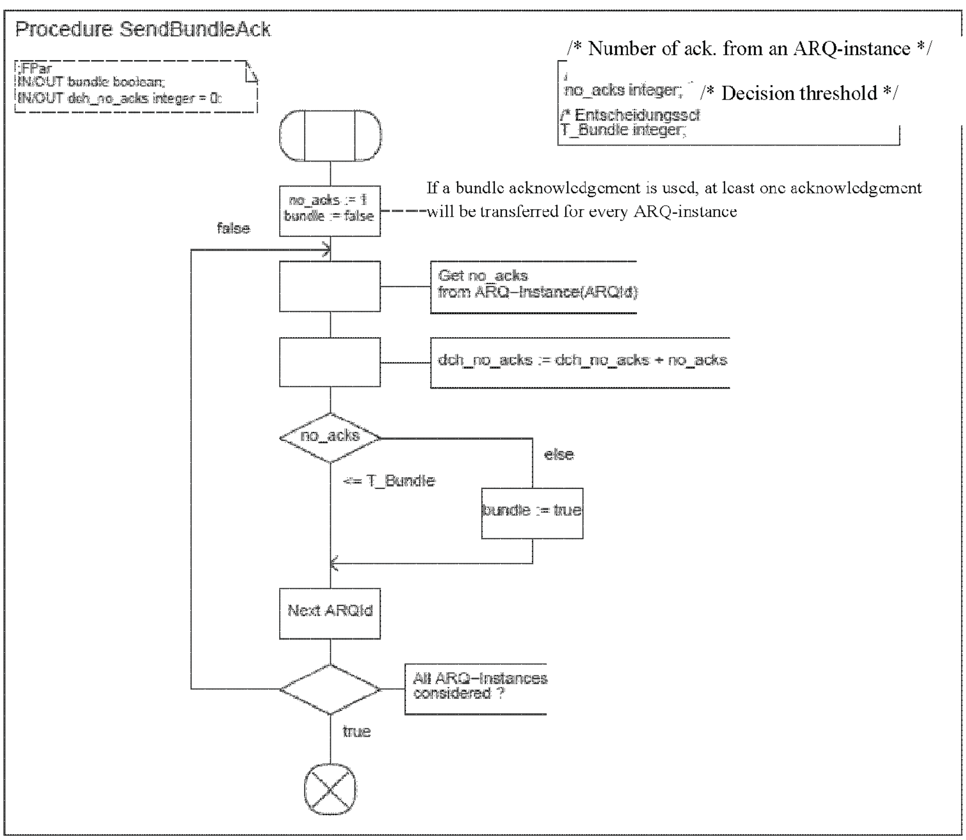


Figure 6.8: SDL-illustration of the algorithm for the transfer of bundle acknowledgements

6.4.1 The bundle acknowledgement

If a long timeslot was reserved, the TCH-handler-object must decide if an ATM-cell is delivered or if this timeslot is used for the bundle acknowledgement (see figure 6.8). For this, the individual ARQ-instances will be queried after each other and share the number of receipts to be delivered. If an ARQ-instance must deliver more than one acknowledgement (thus, negative acknowledgements), it is checked to see if this number of acknowledgements increases a threshold defined by the parameter T_{Bundle}

$$N_{ARQ-Ack} > T_{Bundle}. \qquad (6.14)$$

If this is the case, the long timeslot for a bundle acknowledgement will be used and within the scope of the capacity of a long timeslot, at least one acknowledgement will be transferred for every ARQ-instance of the DCH. Since this type of acknowledgement transfer required channel capacity, which is then no longer available to the ATM-cells and the partner instance can react to this acknowledgement at earliest in the next signaling period, this type of acknowledgement transfer is only possible once per signaling period for each DCH.

6.4.2 Determination of the SREJ to be delivered

If transfer repeats through SREJs or FSREJ-acknowledgements must be requested through the ARQ-protocol, the LLC-scheduler determines for the case of multiple waiting SREJ-acknowledgements the negative acknowledgement to be sent in the current timeslot. Within a signaling period, the SREJs are sent cyclically, whereby the most urgent is started with. Since only within the next signaling period can the acknowledgements be reacted to, it makes more sense to send the waiting SREJs in a row than to transfer only the most urgent SREJ-acknowledgement piggyback. At the beginning of the signaling period, which is shared with the ARQ-instances, the pointer for the SREJ to be sent will be placed again on the most important SREJ acknowledgement. Due to the chronological order of the ATM-cells, this is always the oldest negative acknowledgement, which is found at the beginning of the receipt window. By the SR/D protocol, a FSREJ-acknowledgement is always delivered, see table 5.1 in chapter 5.

6.4.3 The channel monitoring

Another service level supporting measures is the channel monitoring. With this mechanism, the assignment of reservations is controlled based on the receipt conditions of the individual terminals. Initially, all DCHs are in the *Normal* (N) condition, see figure 6.9.

By the composition of the Period-Ctrl-PDU, the TCH-Handler-object is told the number of reservations for this DCH. After completion of the transfer in this period, it is evaluated to see in which timeslots the uplink was received. If all timeslots of a terminal are disrupted, it is assumed that this terminal is in a fading hole and cannot temporarily receive. For this terminal, the status is changed to *Poll* (P) (condition transfer (1)). In this condition, the DCH is no longer considered by the scheduler, but rather

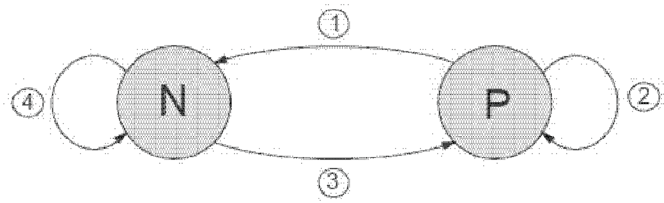


Figure 6.9: Condition transition diagram from the channel monitoring

only a short poll-timeslot is inserted in each signaling period. If at least something was received in a timeslot, then the DCH will remain in the status *Normal* (status transition (4)). If the DCH is in the *Poll* status and if something from the assigned terminal is received in the short poll timeslot, it will be changed back into the state *Normal* (state transition (3)), otherwise the DCH remains in the state *Poll* ((2)).

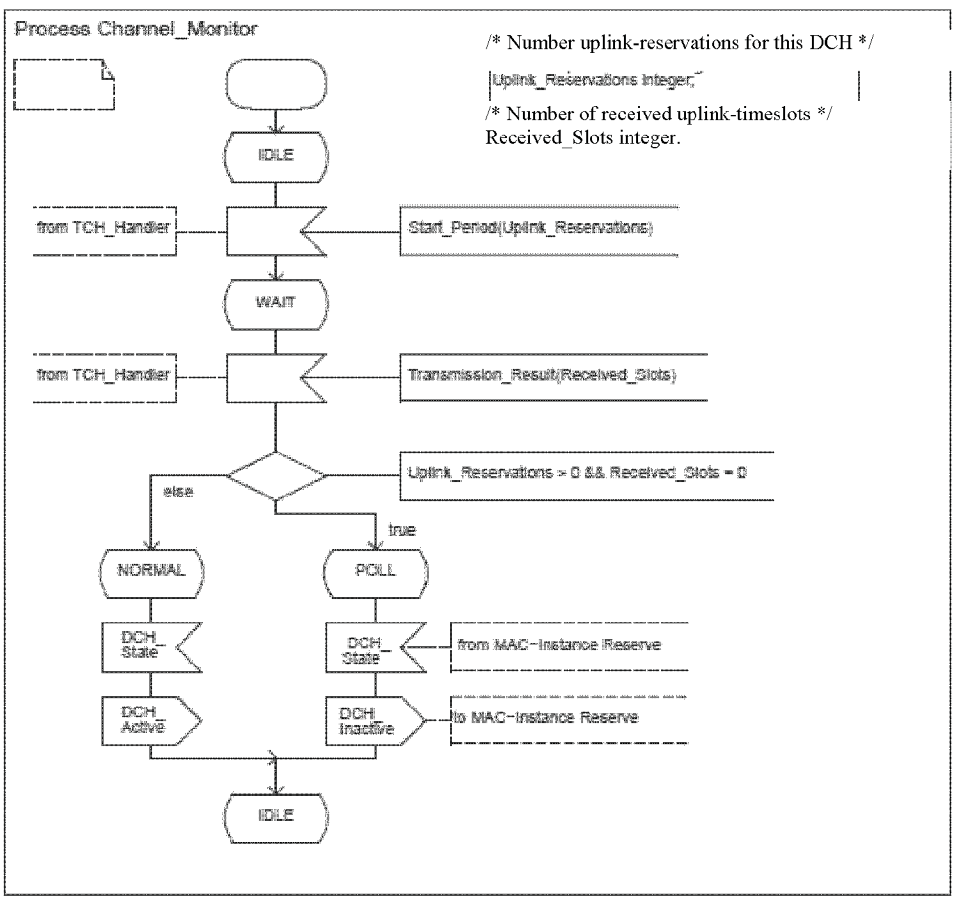


Figure 6.10: SDL-illustration of the process of the channel monitoring

Figure 6.10 shows a SDL-illustration of the channel monitoring process. This process

communicates with the TCH-handler-object and with the reservation process of the MAC-instance (see figure 6.5), which queries the channel state for every single DCH (Signal DCH_State). The monitoring process answers corresponding with DCH_Active or DCH_Inactive. From the TCH-handler-object, the number of uplink reservations (Signal Start_Period (Uplink_Reservations) and the number of uplink timeslots for every DCH is shared in which it was received (Signal Transmission_result(Received_Slots)).

6.5 Investigated and evaluated parameters

Before the simulation model used in the next chapter is described and the results of the performance evaluation of the algorithms is presented, the investigated parameters will be summarized again and characterized in detail.

Parameter	Description
N_{ARQ}	Size of the ARQ window
$N_{Res\,max}$	Maximum number of reservations
$N_{Ack-PCTRL\,max}$	Maximum number of acknowledgements in the Period-Ctrl-PDU
$P_{T\,poll}$	Priority threshold for short poll timeslots
$P_{T\,RACH}$	Priority threshold for the acknowledgement transfer in the random access
T_{Bundle}	Threshold for the transfer of a bundle acknowledgement in a long timeslot

Table 6.3: Parameter of the acknowledgement algorithm in the MAC-Scheduler

While the maximum number of reservations, the maximum number of acknowledgements in the Period-Ctrl-PDU and the threshold for the transfer of a bundle acknowledgement are countable values, which can vary within a reasonable limit, it must be observed by the determination of the priority thresholds similar as with the determination of acknowledgement priorities that the different service level requirements of the individual virtual connections must be considered if the acknowledgements of these connections compete with each other in the scheduler. On the other side, in particular the maximum possible delays can be partially used if the service level requirements are better fulfilled with a high-prioritized connection. That is why the thresholds for the service evaluation were selected depending on the maximum delay $\tau_{d\,max}$ of the individual virtual connection. Thus, for the priority threshold that controls the insertion of the short poll timeslots the following applies

$$P_{T_{poll}} = p \cdot \tau_{d_{max}} \quad \text{mit} \quad 0 \leq p \leq 1 \tag{6.15}$$

and for the threshold that determines if a random access is triggered due to an acknowledgement transfer, the following applies

$$P_{TRACH} = q \cdot \tau_{dmax} \quad \text{mit} \quad 0 \leq q \leq 1 \tag{6.16}$$

CHAPTER 7

Integrated stochastic simulation model for the system analysis of the W-ATM-wireless interface

In order to be able to execute a detailed evaluation of the protocols of the W-ATM-wireless interface and the service level supporting measures developed in this work on the basis of basic conditions being as realistic as possible, the protocol plane is implemented in a stochastic simulation model, which illustrates the real basic conditions, for example, the application processes and the ATM-traffic created by them along with the properties of the wireless transmission with the help of ideal models. In addition to the determination of the characteristics for the eservice evaluation, the simulation model serves as a *protocol debugger* for the validation of the functionality of the protocol plane and the service level supporting measures during the development phase.

7.1 Software architecture of the simulation model

The modeling of the time system behavior occurs with the help of the event-controlled simulation. The software architecture of the developed simulation model is illustrated in figure 7.1. An object-oriented approach is followed by which the communication objects are embedded in the model environment. A communication object contains the protocol plane (see chapter 4) of a terminal or the base station, load generators for the creation of the ATM-traffic to be carried and a modem-object, which illustrates the behavior of the digital transfer system and connects the protocol plane with the wireless channel

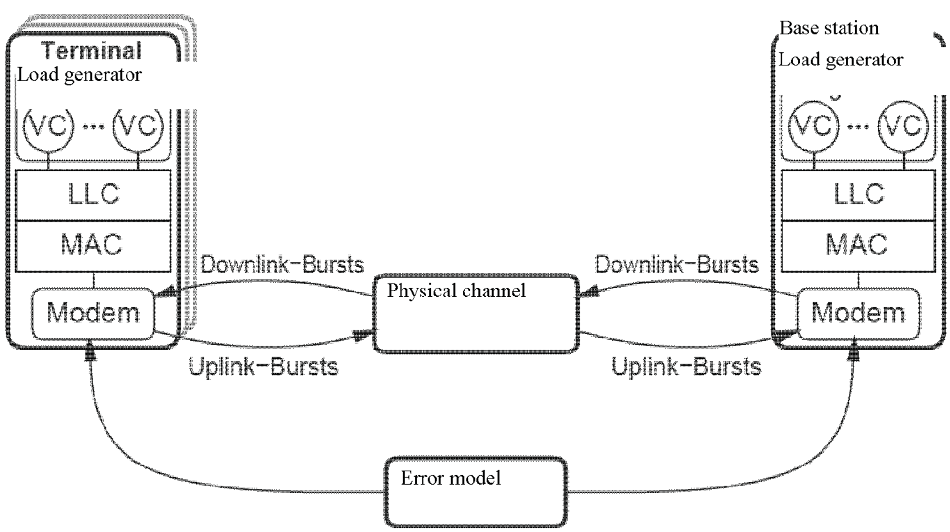


Figure 7.1: Module of the SIMCO3++/W-ATM-simulator

The properties of the wireless channel are illustrated through two objects. The object *physical channel* models the time aspects of the delivery of physical bursts. It recognizes collisions based on the transmission and reception times of bursts and forwards bursts to the receiving modem. Through the *error model* object, the transmission error, which was caused by the wireless distribution and interferences, is shown.

7.2 Modeling of the application processes

The application processes are the virtual connections and their source processes, whose ATM-cells are transferred through the wireless interface. The source processes are characterized by ATM-cell streams created by them and the service levels required by them.

The modeling of typical ATM-traffic sources occurs through the illustration of the basic cell generation processes through ideal stochastic processes with which the temporary arrival times of ATM-cells are determined. The Assumptions about the behavior of traffic sources has a crucial influence on the system performance. The starting point for different source models are the ATM-applications listed in table 2.1 and their allocation to the ATM-service classes.

The selection of ideal sources and simulation scenarios occurs with the reverse objectives of modeling realistic basic conditions and simultaneously being able to analyze the effects of changes between source properties and system performance. The modeling of the source traffic is restricted to a typical application per service class, whereby the used source model is scalable in regards to its characteristic size (i.e. data date) and its service level requirements (i.e. maximum delay).

7.2.1 The deterministic stochastic process as a model for CBR-sources

The crucial property for the modeling of CBR-services is the deterministic temporary arrival time of cells. CBR-sources can clearly be described through their average cell generate rate λ . Table 7.1 show the parameterizing of the CBR-source for two cases of application.

Application	λ	τ_{dmax}	$\frac{\tau_{dmax}}{\tau_{slot}}$	CLR
PCM-language	$64\ \mathrm{kbit/s}$	$2\ \mathrm{ms}$	100	10^{-3}
ISDN-primary multiplex connection*	$2.048\ \mathrm{Mbit/s}$	$5\ \mathrm{ms}$	250	10^{-4}

*With the use as a radio-local-loop-system for the connection of an ISDN-extension system

Table 7.1: CBR-applications and the parameterizing of the CBR-source

7.2.2 The Poisson-process as a model for VBR-sources

An arrival process A(t) is labeled as a Poisson-process if its temporary arrival times are independent and belong to a negative-exponential distribution (see i.e. (31))

$$A(t) = 1 - e^{-\lambda t}, \quad t \geq 0. \tag{7.1}$$

For expected value, variance and variation coefficient, the following applies:

$$E(A) = \frac{1}{\lambda}, \qquad Var(A) = \frac{1}{\lambda^2}, \qquad c_A = 1 \tag{7.2}$$

If you observe the process during a constant time span t, the number X of observed arrival events follows a Poisson distribution. The number of arrivals is independent in any time intervals (property of the memory loss). If you observe the Poisson-process during a random timeframe of the length $\Gamma = \tau$, the following must be observed for the probability X = I events

$$P(X = i|\Gamma = \tau) = \frac{(\lambda\tau)^i}{i!} e^{-\lambda\tau}. \tag{7.3}$$

The average number of arrivals in the time section τ is defined as $\lambda \cdot \tau$, thus the parameter λ is labeled as the arrival rate.

The Poisson-process is used as a simple to model stochastic process for sources of the VBR-service class and due to its flexible setting, it allows for the targeted investigation of the effect of certain parameters. Here the high variation of the temporary arrival times is used, which provide particularly strong requirements for the MAC-protocol. Due to the memory loss, other models, like the video source described in the following must be used for the creation of correlated source traffic.

7.2.3 Video source with autoregressive process as model of a typical VBR-application

The modeling of a typical application from the VBR service occurs with a video source. It uses the autoregressive process described in (25) (see figure 7.2), which describes the cell stream of a VBR-video codec with a high image quality. The model affects measurements of a real video telephony scene in which the codec has created 30 images per second with an average data rate of 3.9 Mbit/s and a burstiness[1] of 2.712. The data rate λ is freely scalable corresponding with the resolution of the image. In the simulator, by default, the rate obtainable with newer codecs of 2 Mbit/s is used. The current data rate λ(n) of the model during the n-th image is calculated with the auto-regression (7.4):

$$\lambda(n) = \max\{a \cdot \lambda(n-1) + b \cdot w(n) \cdot \lambda, \ \ 0\} \tag{7.4}$$

Here w is a gauss-distributed random variable with $E(w)$ = 0.572 and $Var(w)$ = 1. It applies a = 0.8781 and b = 0.2131.

[1]Ratio of maximum to average bit rate

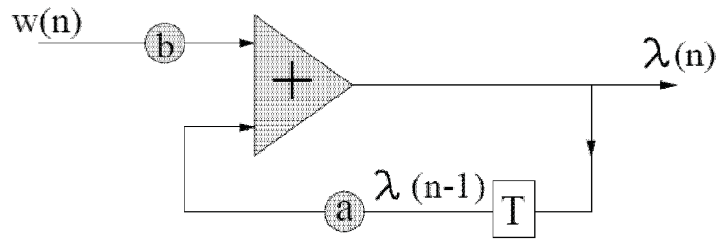


Figure 7.2: Autoregressive process of first order

7.2.4 Time-uncritical ABR and UBR services

The arrival process of the ABR/UBR sources only has an insignificant influence on the system performance. Its property is nearly lost during the high load phases due to the waiting times during the transfer of higher-prioritized ATM-cells of CBR/VBR connections. In the simulator, the ABR/UBR load therefore results from Poisson sources, which generate ATM-cells with negative-exponentially distributed temporary arrival times in accordance with a predefined average rate.

7.3 The physical channel

The model of the physical channel is the central object in the system model. It serves as a transport medium through which the entire message exchange occurs between the terminal and the base station. The delivery of messages occurs with burst objects, which contain a MAC-PDU and are marked through the transmitter position and the start and end time. The resolution of the time axis is based on the timeslot length. With correct system behavior, bursts cannot exceed the limits of the timeslots. The model neglects the time expansion of transmitting signals and the usage of protection times between bursts. If multiple bursts are delivered in the same timeslot (i.e. with random access), the channel will report a collision.

7.4 Transfer error

The error model illustrates the time-variable influence of the wireless channel and the digital transfer system on the transfer of physical bursts. The influences on the expansion of the waves like multi-path expansion, shading, distance-dependent path losses and interferences depend strongly on the environment and the mobility. Due to the variety of possible areas of application for W-ATM-systems, a very different behavior may be the result in the concrete case.

In the simulator, the modeling of the wireless channel is restricted to the illustration of transfer errors, which are lost through the MAC-PDUs contained in bursts. With a broadband channel, due to the multi-path expansion, there are level breaks, which are labeled as shrinkage (multipath-fading) and lead to cluster-like transfer errors. Since on a TDD-channel the wave expansion is symmetric in both transfer directions, the transfer errors are observed as correlated on the uplink and downlink.

7.4.1 Uncorrelated channel error

For comparison investigations, a channel model was implemented, which generates the uncorrelated package error with a predefined probability P_{err}. For this, by the receipt of a burst, a similarly distributed random number x is drawn from the interval (0..1).

If the condition

$$x < P_{err} \tag{7.5}$$

is fulfilled, the burst will be discarded as disrupted. In contrast to the Gilbert-model described in the following, the package error of this model is statistically independent.

7.4.2 The Gilbert-model for correlated channel errors

A typical property in digital wireless channels is the cluster-like collection of transfer errors. Gilbert suggests in (5) a channel model, which is based on a Markov condition model with two conditions. In the condition G (GOOD), the channel is error-free, while in the condition B (BAD) package errors occur with the probability P_e. Due to the expansion conditions by 5.2 GHz, it is assumed that in the bad state all bursts are disrupted and thus all PDUs are lost (P_e = 1.0). The transitions between the two conditions are triggered through memory-less processes with the transition types $\lambda_{G,B}$ and $\lambda_{B,G}$, see figure 7.3.

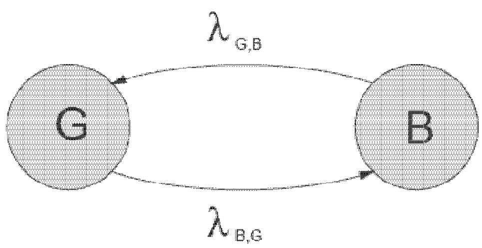


Figure 7.3: Gilbert-error-model

For the execution of the performance evaluations, this error model must be set, whereby the exact illustration of the real channel properties is subordinate for the investigation of the protocols, because on the one hand the investigated systems are used in different environments and on the other hand, the protocols must be designed without this so that they can work on transfer channels with different error properties. That is why and due to the lack of concrete measuring values for the used wireless channel, the following estimation is executed for the setting of the error model, by which it was assumed that with a mobility $v = 5km/h \approx 1.39m/s$, altogether 2.5% of all packages are disrupted (P_{err} = 0.025) and are therefore lost:

The wavelength with a frequency of 5.2 GHz follows with the light speed c to

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^5 \frac{km}{s}}{5.2\,GHz} = 5.77\,cm \tag{7.6}$$

Shrinkage occurs through destructive interference, thus, half of the wavelength is used for the distance of the level breaks d

$$d_{fade} = \frac{\lambda}{2} = 2.885\,cm. \tag{7.7}$$

For the time distance, the level breaks follow by the accepted mobility of $v \approx 1.39m/s$

$$t_{fade} = \frac{d_{fade}}{v} = \frac{2.885 \cdot 10^{-2}m}{1.39\frac{m}{s}} \approx 2.0 \cdot 10^{-2}s. \tag{7.8}$$

This results in a stay duration in the bad condition, corresponding with the duration of the level break

$$t_{err} = P_{err} \cdot t_{fade} = 0.025 \cdot 2.0 \cdot 10^{-2}s = 500\,\mu s. \tag{7.9}$$

This corresponds with the transfer duration of 25 ATM cells based on the gross data rate of 50,000 ATM cells. For the stay duration in the good condition, corresponding with the duration of the error-free transfer, the following comes

$$t_{good} = (1 - P_{err}) \cdot t_{fade} = (1 - 0.025) \cdot 2.0 \cdot 10^{-2}s = 19500\,\mu s, \tag{7.10}$$

which corresponds with the transfer duration of 975 ATM cells, this means with an average period length of 20 timeslots, 48 periods are undisturbed on average. In accordance with the Gilbert-model, the stay durations are distributed negatively-exponentially with the average values t_{bad} or t_{good}.

7.5 Implementation aspects

For the implementation of the functions and algorithms of the simulation model, the object-oriented programming language C++ is used. Here the SIMCO3++/W-ATM simulation environment was created. The basic elements of the stochastic simulation, i.e. the event-oriented simulation control, the random number generators and the LRE-algorithm for the statistic evaluation are provided by the C++-class library *Communication Network Class Library* (CNCL) (15).

The implementation of the protocol plane occurs corresponding with the ISO/OSI reference model. For communication between the individual layers, service-primitive objects are used, which are exchanged through service access point objects, whereby the C++-classes of the SIMCO-class library are used (20). These objects form clearly defined interfaces between the layers and promote the exchangeability and reusability of the implemented protocols.

CHAPTER 8

Performance evaluation

The service level supporting measures introduced in chapter 6 were implemented in the stochastic simulation model and the effects of the individual measures were initially quantified based on the special scenarios. In a second step, a performance evaluation of the complete system was executed with the usage of realistic scenarios. In this chapter, after determination of the evaluation goals and a few explanations about the statistical significance, the results are summarized.

8.1 Evaluation goals and service numbers to be determined

The evaluation goal of this work is the effect of the executed measures on the service levels of individual virtual connections from different ATM-service classes for a specified traffic scenario based on to-be-determined performance numbers.

8.1.1 Performance numbers for real-time oriented CBR/VBR connections

The characteristic service level parameters for real-time oriented CBR/VBR connections are the average cell delay CTD and the cell loss ratio CLR, see chapter 2.4. With the usage of an ARQ-protocol and neglect of non-recognized bit errors, cell losses only occur through schedule exceeding and the discarding of cells. Schedule exceeding exists if the transfer delay of an ATM-cell exceeds the maximum cell delay $\tau_{d\,max}$.

The cell delay and the schedule exceeding ratio are illustrated in the form of complementary distribution functions (CDF) or minimum value distribution functions $P(\tau_d > t)$ (also written as $P(> \tau_d)$)(34). These distribution functions specify the share of cells, whose delay exceeds a certain value. With the predefined $\tau_{d\,max}$, you can read the resulting schedule exceeding ratio on the ordinate, see figure 8.1.

8.1.2 Performance numbers for time-uncritical ABR/UBR connections

For time-uncritical ABR/UBR connections, no requirements are made for the cell delays. The characteristic number is thus the maximum obtainable cell throughput ρ_{max}, standardized on the gross data rate of 50,000 ATM cells per second. The number $O = 1 - \rho_{max}$ is marked as a protocol overhead. That is the share of the channel capacity, which is filled through the transfer of internal control and signal messages and is therefore not available for the transfer of ATM-cells. This number is an object of future investigations and will not be further considered in the following.

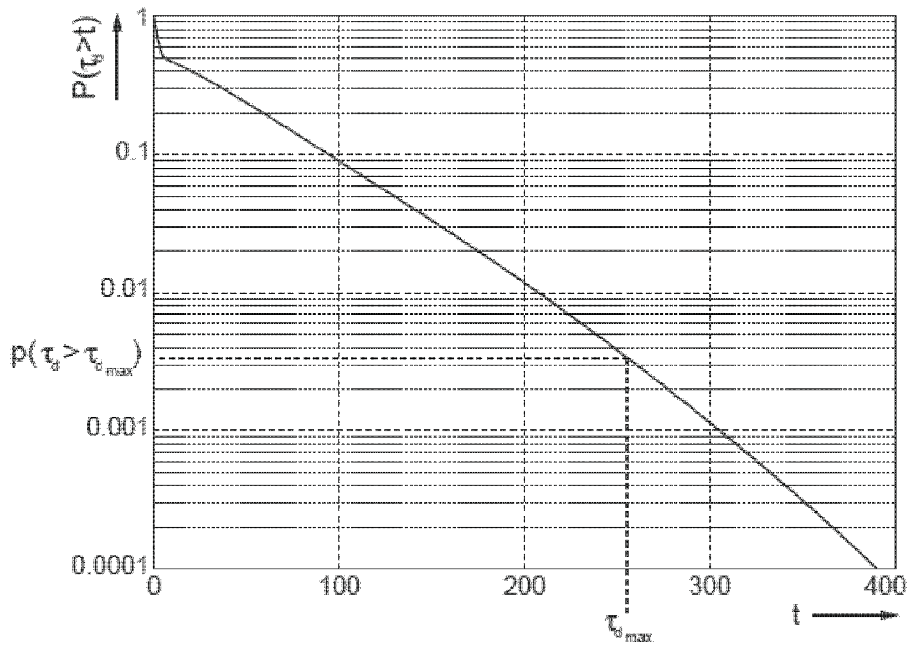


Figure 8.1: Reading of schedule exceeding ratio $P(> \tau_{d\,max})$from the complementary distribution function of the transfer delays with the defined maximum cell delay $\tau_{d\,max}$

8.2 Statistical certainty of the simulation results

With stochastic simulation investigations, the statistical uncertainty of the results must always be considered, in particular for rare events. By all executed simulations, the LRE-procedure (*Limited Relative Error*) was used for the statistical evaluation (27,28), which provides an error statement and quantifies the increased need for random samples due to correlations, which are caused in the investigated scenarios through correlated source traffic and correlated channel error. Due to the considerable correlation and the need for a random sample resulting from this, a relative error of 5% was given for the LRE-algorithm for the events with the smallest probability, which, however, still led to simulation times of up to 2 days at modern high-performance workstations.

8.3 The ideal ARQ-protocol

For the evaluation of the individual service level supporting measures, specifically the acknowledgement strategies, a so-called *ideal ARQ-protocol* was implemented in the simulation environment. Ideal stands here for an ideal acknowledgement transfer. The I-frames were acknowledged in this protocol directly through the function calls, this means no acknowledgements are transferred through the wireless channel. For all other functions of the protocol plane, the real model is still used. Since the lack of a frame can first be noticed upon receipt of the following frame, the recipient tells the transmitter in the ideal ARQ-protocol before the structure of a new signaling period which frames are missing. Through the TDD-procedure, this point in time in terms of the acknowledgement transfer is still to be seen as ideal, because without this, a negative acknowledgement can first be reacted to in the following signaling period.

The missing acknowledgement transfers only burden the channel. This effect was neglected by the following observations. The delay curves, which are measured under the use of the ideal ARQ-protocol, therefore illustrate a theoretical lower limit for the delay, a type of "Shannon-limit" so to say for the acknowledgement procedure investigated here, which shows the possible need for optimization for the strategies.

8.4 Bigger delays for uncorrelated channel errors

A lot of the following investigations were executed for a wireless channel with correlated channel errors and for one with uncorrelated channel errors. Here it is shown that the end-to-end delays of the ATM-cells are normally greater for uncorrelated channel errors. This has two primary causes:

- The event that a terminal does not receive the Period-Ctrl-PDU and thus all bursts from the downlink in this period are lost, is statistically independent for uncorrelated channel errors from the event that an individual burst is disrupted. With correlated channel errors in contrast, it is very probably that after receipt of the Period-Ctrl-PDU, all downlink bursts can be received or that after the loss of the Period-Ctrl-PDU, all downlink bursts are disrupted. Since by the executed investigations, however, the average share of loss packages for correlated and uncorrelated channel errors is assumed as equal in size, there are larger delays by uncorrelated channel errors, because here effectively more packages are lost and the loss of the Period-Ctrl-PDU does not "cover" the disruptions of downlink bursts. On the uplink, there are higher delays, because with the packages on the downlink, the acknowledgements for the I-frames of the uplink are also lost. In the end, a higher load is caused due to the acknowledgement transfers and transfer repeats.
- The investigated SR/D-ARQ-protocol uses a REJ-acknowledgement in order to request the transfer repeat of multiple I-frames at once. Since with correlated channel errors the loss of the I-frames occurs in a correlated manner as well, multiple frames can be requested through a REJ-acknowledgement. With uncorrelated errors, the bursts are disrupted sporadically so that the distribution of the lost I-frames is much greater and the "bundle gain" is smaller through the REJ-acknowledgement. This makes the delivery of a larger number of negative acknowledgements required, which in turn leads to larger delays.

8.5 Explicit, implicit discarding and the different levels of the discarding

The existence described in section 5.5 of long waiting times by implied discarding is quantified in the following based on the delay of all N-PDUs of a Poisson scenario with a total load of 95%, which is distributed variable to 10 terminals (see table 8.1). The offer of a connection describes the traffic created from the source in one direction, while the total offer on the channel includes the uplink <u>and</u> downlink.

Number of terminals	10
Connections per terminal and direction	1
Service class	VBR
Standard offer λ_i of connection *i*	$\sum \lambda / 2^{i+1}$
Maximum delay $\tau_{d\,max}$	$200\ \tau_{slot} \hat{=} 4\ ms$
Size of the ARQ-window	32
Channel error	2.5% correlated
Standard total offer $\sum \lambda$	≈ 0.95

Table 8.1: Parameter of the Poisson scenario with improperly distributed load

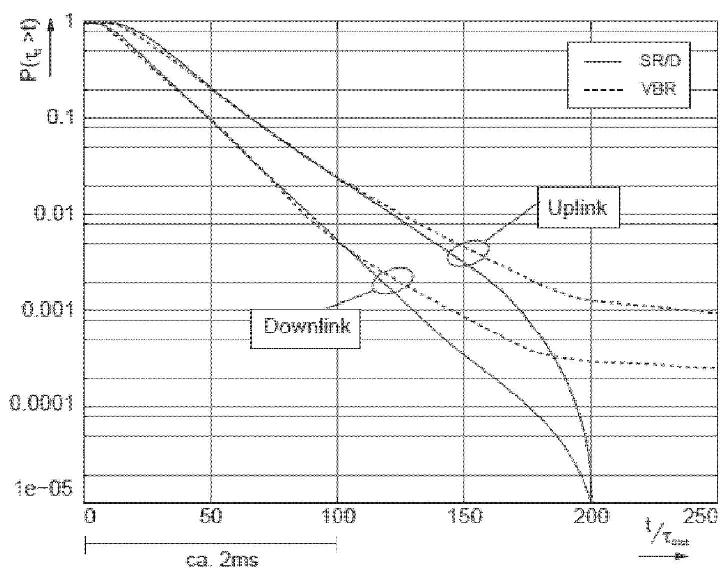


Figure 8.2: High delays with implied discarding

From table 8.2, it can be seen that the cell loss ratio for both procedures of the discarding is in the same classification. The schedule exceeding ratios in contrast are a degree higher for the procedure of the implied discarding, which clearly shows the long waiting times in the receiver. If these wait times exist in the transmitter due to high traffic load on the channel, after expiration of their schedule, so before delivery, the cells are discarded, which can then be noticed in the cell loss ratio.

	Implicit discarding		Explicit discarding	
	Downlink	Uplink	Downlink	Uplink
CLR	$5.18 \cdot 10^{-5}$	$3.5 \cdot 10^{-4}$	$8.71 \cdot 10^{-5}$	$1.8 \cdot 10^{-4}$
$P(\tau_d > \tau_{dmax})$	$2.95 \cdot 10^{-4}$	$1.27 \cdot 10^{-3}$	$5.0 \cdot 10^{-6}$ *	$1.9 \cdot 10^{-5}$

*This value serves only for the orientation and due to the limited number of executed simulation steps, it is not statistically certain.

Table 8.2: Cell loss and schedule exceeding ratios

Table 8.2 and figure 8.2 clearly show the long wait times of the N-PDUs and the comparably low service level, which can be reached for this scenario with the procedure of the implicit discarding. Thus, in the following only the procedure of the explicit discarding is considered.

Provided a high load scenario (95% total load) with symmetrically distributed load (see table 8.3), the effects of the different procedures are observed for the discarding of ATM-cells, see section 5.3.1. The premature transfer of received cells to the next higher protocol layer is controlled through a so-called *Forward-Timer*. In amendment to the investigations in (9), the complete protocol plane was observed here.

Number of terminals	10
Connections per terminal and direction	1
Service class	VBR
Standard offer λ_i of connection *i*	0.0475
Maximum delay $\tau_{d\,max}$	$200\ \tau_{slot} \mathrel{\hat{=}} 4\,ms$
Size of the ARQ-window	32
Channel error	2.5% correlated
Standard total offer $\sum\lambda$	≈ 0.95

Table 8.3: Parameter of the Poisson scenario with equally distributed load

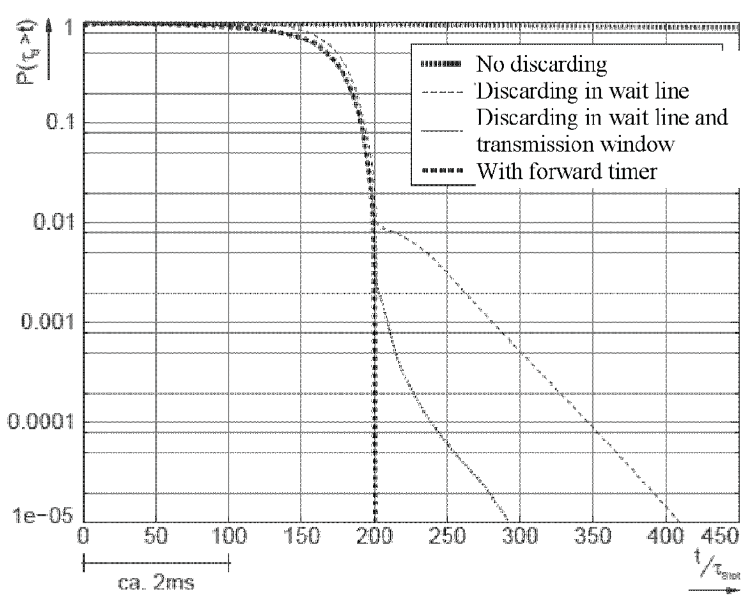


Figure 8.3: Different levels of discarding

From figure 8.3 and table 8.4, you can see that through discarding, relatively few cells that have exceeded their schedule already significantly relieve the channel and dramatically improve the service level. Here it must be observed that if a discard is done in the waiting line and transmission window, only the cells in the schedule exceeding ratio come in if their schedule expires in the receiver, because they otherwise they would not have been transferred at all in the first place.

Procedure	Discarded cells	$P(\tau_d > \tau_{dmax})$
No discarding	0%	99.96%
Discarding in waiting line	1.7%	1.2%
Discarding in waiting line and transmission window	2.4%	0.39%
With forward timer	2.4%	0%

Table 8.4: cell loss and schedule exceeding ratios for the different levels of discarding

By the observation used here, these cells are not included in the cell loss ratio, because they are not counted as discarded by the receiver.

8.6 Performance evaluation of the acknowledgement procedure

The performance evaluation of the acknowledgement procedure was executed based on the special scenarios by which the influence on the investigated parameters clearly occurred. For the modeling of VBR-sources, here, as in section 8.5, Poisson sources were used. For the complementary distribution functions illustrated in this section, the LRE-error is up to a probability of 10^{-4} smaller than 5%. However, probabilities up to 10^{-5} were still shown in order to illustrate the further sequence to compare the graphs.

8.6.1 LLC-acknowledgements in the Period-Ctrl-PDU

The influence of the acknowledgement transfer in the Period-Ctrl-PDU to the delay of the ATM-cells was inspected based on a scenario with 13 terminals from which 10 terminals only operate uplink connections and 60& of the load combine. 3 other terminals only operate downlink connections with a total load of 15%, see table 8.5.

		Terminal 1-10	Terminal 11-13
Standard downlink offer	λ_d	0.0	0.05
Standard uplink offer	λ_u	0.06	0.0
Connections per terminal		1	
Service class		VBR	
Source type		Poisson	
Maximum delay	τ_{dmax}	$250\ \tau_{slot} \mathrel{\hat{=}} 5\,ms$	
Size of the ARQ-window		32	
Standard total offer	λ	≈ 0.75	

Table 8.5: Poisson-scenario 60% uplink and 15% downlink load

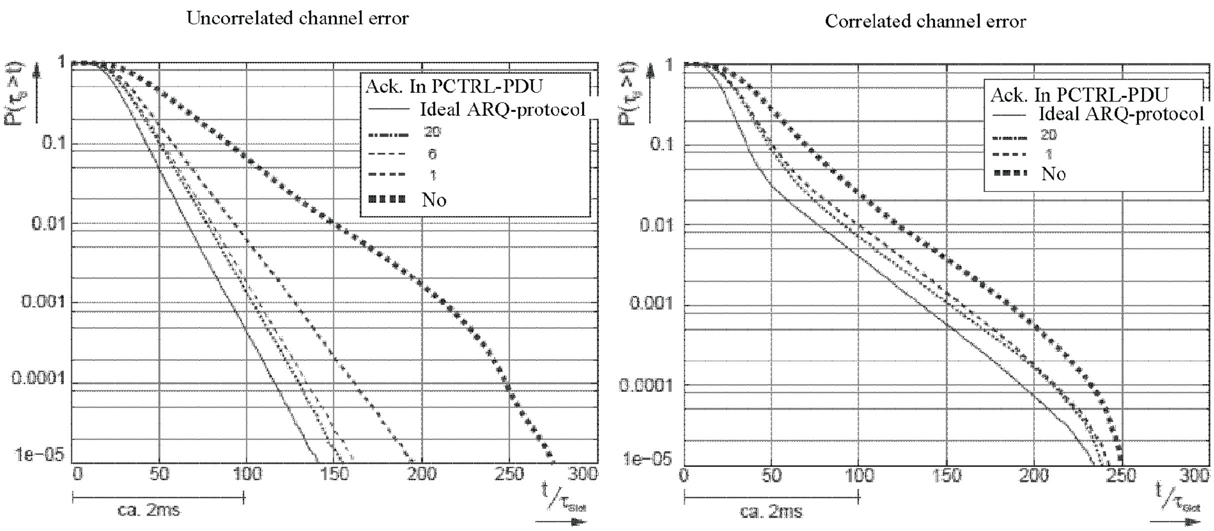


Figure 8.4: Effects of the acknowledgement transfer in the Period-Ctrl-PDU

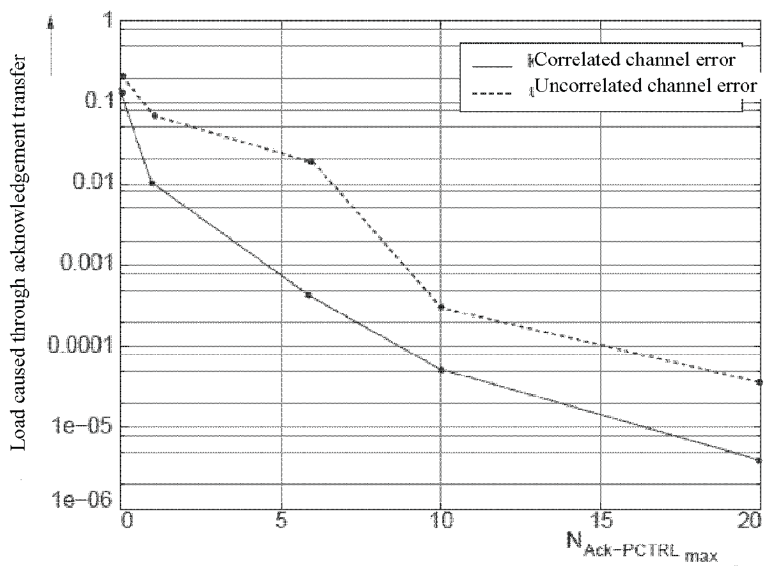


Figure 8.5: Load caused through acknowledgement transfer on the downlink depending on the acknowledgement number in the Period-Ctrl-PDU

The varied parameter $N_{Ack-PCTRL\ max}$ is the maximum number of LLC-acknowledgements, which can be sent with the Period-Ctrl-PDU, see table 6.3. For reasons of simplification, it was assumed that the number of reservations that can be transferred will not be reduced for an acknowledgement number greater than 6. Figure 8.4 shows the effects on the end-to-end delays of all N-PDUs from the uplink with uncorrelated channel errors and with correlated channel errors. For comparison, the delays are illustrated as a lower limit if they arise during the usage of the ideal ARQ-protocol and thus do not have their cause in the acknowledgement transfer. It shows that already during the transfer from only one acknowledgement in the Period-Ctrl-PDU, the delays decrease clearly. Delays greater than

$250\ \tau_{Slot}$ (for graph “None”) arise through cells in the receiver, whose schedule is exceeded during the waiting for the transfer repeat of a frame with a lower sequence number.

For 6 acknowledgements (this is how large the field of the Period-Ctrl-PDU is, see table 4.2), the delay further decreases. The gain from 6 to 20 acknowledgements is minimal in contrast, with correlated channel errors the graphs in figure 8.4 are on each other for 6 and 20 acknowledgements. The delays from the downlink are not observed here, because the downlink is not (yet) considered through the increased acknowledgement transfer in the monitoring frames. Which loads are causing these monitoring frames is illustrated in figure 8.5. Here the load caused through the acknowledgement transfers is entered over the number of acknowledgements, which can be delivered in the Period-Ctrl-PDU. Already the transfer of just one acknowledgement in the Period-Ctrl-PDU relieves the channel significantly (if you observe the logarithmic illustration in figure 8.5).

8.6.2 The insertion of short poll timeslots

The influence of the acknowledgement transfer through the dedicated insertion of short poll timeslots (see section 6.2.3) was investigated with the help of the scenario from table 8.6, whereby the total load for the downlink was determined at 48%. Compared to the investigations for the number of acknowledgements in the Period-Ctrl-PDU; the load was reduced by 25% in order to not get in a case of overload, because the insertion of a short poll timeslot costs a fourth of the capacity of a long slot.

		Terminal 1-10	Terminal 11-13
Standard downlink offer	λ_d	0.048	0.0
Standard uplink offer	λ_u	0.0	0.05
Connections per terminal		1	
Service class		VBR	
Source type		Poisson	
Maximum delay	τ_{dmax}	$250\ \tau_{slot} \hat{=} 5\,ms$	
Size of the ARQ-window		32	
Standard total offer	λ	≈ 0.63	

Table 8.6: Poisson scenario with 15% uplink and 48% downlink load

The effects of the acknowledgement transfer with the help of the short timeslots are covered partially through effects from the MAC-protocol, which also uses random access to transfer the capacity requirements to the uplink and constantly transfers an acknowledgement. In the simulations, the parameter p was varied, which is combined with $P_{T poll}$ over the maximum delay

$$P_{T poll} = p \cdot \tau_{dmax} \quad \text{mit} \quad 0 \leq p \leq 1. \tag{8.1}$$

Here $p = 0.1$ means that a short poll timeslot is inserted if a time span that corresponds with 90% of the maximum delay was already waited for with the acknowledgement. From figure 8.6, it can be seen that the dependency of the delay from the parameter $P_{T poll}$ is low for this special scenario. For the evaluation of the effects of this parameter with correlated channel errors, other investigations

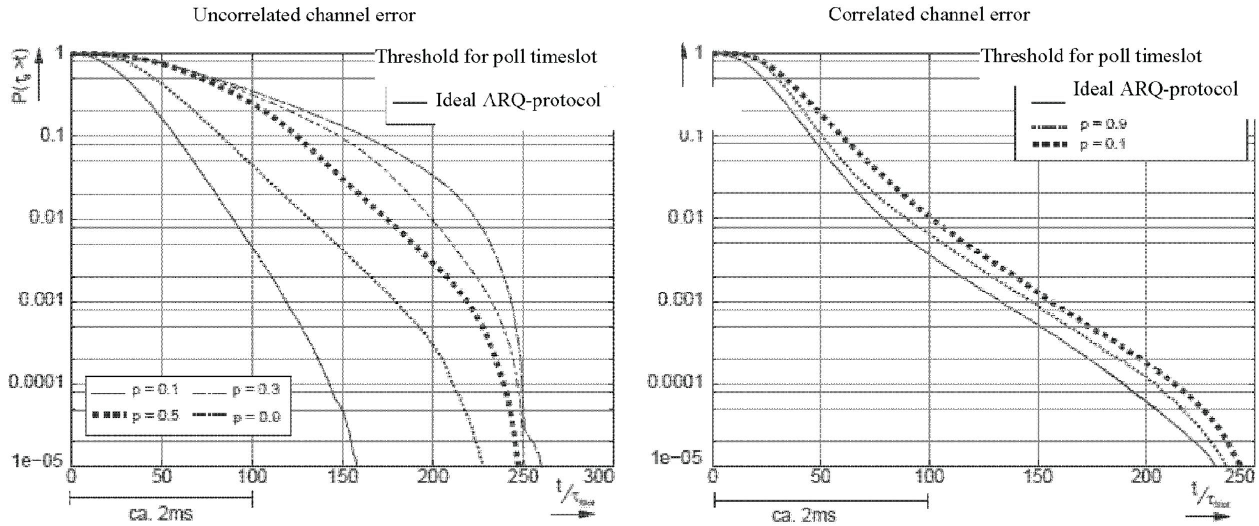


Figure 8.6: Effects of the threshold, which controls the insertion of the short poll timeslots to the delays of the downlink

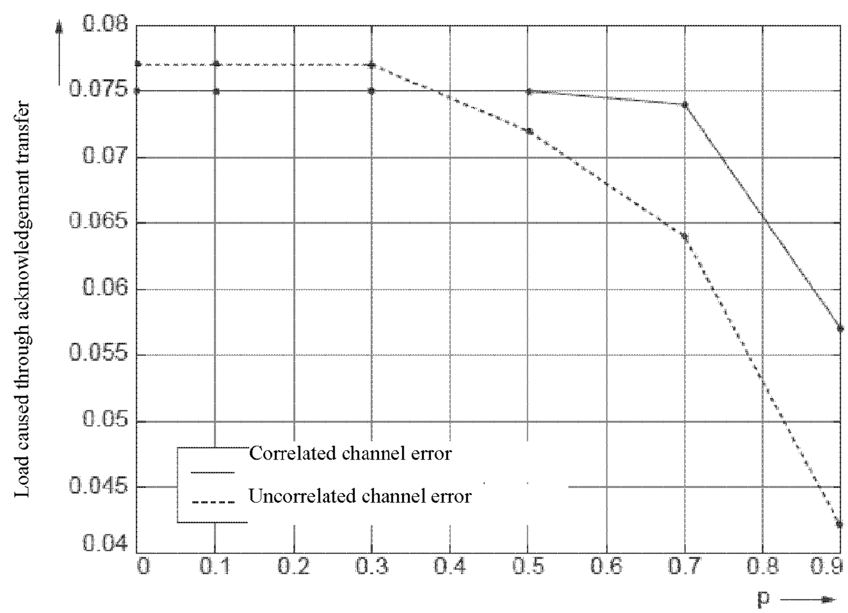


Figure 8.7: Load caused by acknowledgement transfer to the uplink depending on p

are surely required, thus, for example, for scenarios with correlated burst-like source traffic, as is caused through video sources, a stronger dependency is to be expected. There is a differentiated image for uncorrelated channel errors. Here the dependency of the delays from these parameters is clearer due to the increased acknowledgement load (see section 8.4). For comparison, the behavior of the system with the usage of the ideal ARQ-protocol is entered in figure 8.6.

In figure 8.7, the standard acknowledgement load on the uplink depending on p is shown (here no short timeslots were inserted for p = 0 due to the acknowledgement transfers). Through the short poll timeslots, this load can be avoided, because the number of monitoring frames that only contain one acknowledgement and are transferred in one long timeslot are increasingly replaced through short poll times lots and thereby relieve the channel. However, this effect depends greatly on the load scenario. For scenarios with symmetrical load or for DCHs that operate parallel connections, the number of monitoring frames is reduced by either transferring an I-frame in the opposite direction or by using a bundle acknowledgement.

8.6.3 Random access due to acknowledgement transfers

The threshold $P_{T\,RACH}$, which specifies after which waiting time a random access will be triggered due to an acknowledgement transfer, is expressed through the parameter q, which is to be varied

$$P_{T\,RACH} = q \cdot \tau_{dmax} \quad \text{mit} \quad 0 \le q \le 1. \tag{8.2}$$

The same scenario as for the investigation of $P_{T\,poll}$ was used. For the base station, there was no possibility to insert short poll timeslots for the uplink. From figure 8.8, it can be seen that the influence of this threshold is negligible at least for this scenario. Also here it applies again that the effects are covered constantly together with the capacity requirements of the acknowledgement transfer occurring.

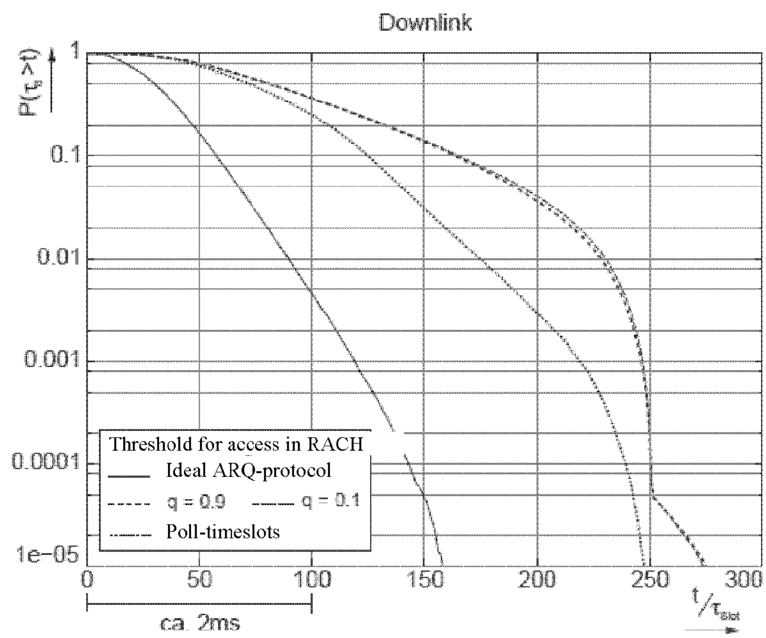


Figure 8.8: Effect of the threshold, which controls the random access due to acknowledgement transfers by uncorrelated channel errors

Another statement from figure 8.8 is that the acknowledgement transfer alone through the random access leads to considerable delays and thus, to losses by the service level. For comparison, figure 8 shows the graph for the delay with the usage of short poll timeslots with $p = 0.5$. The bending of the graph at $t = 250\ \tau_{Slot}$ is caused by the I-frames, which wait in the receipt window for I-frames with lower sequence numbers and exceed their schedule here before they can be given to higher protocol layers. From figure 8.8, it is clear that it is inadequate for the service level requirements of the connections in this scenario to only transfer the acknowledgements in the random access.

8.6.4 The bundle acknowledgement

For the bundle acknowledgement (see section 6.4.1), the parameter T_{Bundle} was investigated, thus the number of waiting (negative) acknowledgements from a virtual connection, based on which it is decided if an assigned long timeslot is used for the transfer of an I-frame or for the transfer of up to 24 LLC acknowledgements. Since the bundle acknowledgement for the downlink, different from the acknowledgements in the Period-Ctrl-PDU, is not transferred in the broadcast mode, its influence on the service level is larger if the terminals operate multiple virtual connections in a parallel manner. Thus, a scenario with 4 mobile stations was selected, which operate 3 connections per terminal and distribute a standard load of 75% symmetrically on all connections, see table 8.7.

Number of terminals	4
Standard downlink offer λ_d	0.375
Standard uplink offer λ_u	0.375
Connections per terminal	3
Standard offer per connection λ_i	0.03125
Service class	VBR
Source type	Poisson
Maximum delay τ_{dmax}	$250\ \tau_{slot} \hat{=} 5\,ms$
Size of the ARQ-window	32
Standard total offer λ	≈ 0.75

Table 8.7: Poisson-scenario with 3 virtual connections per terminal

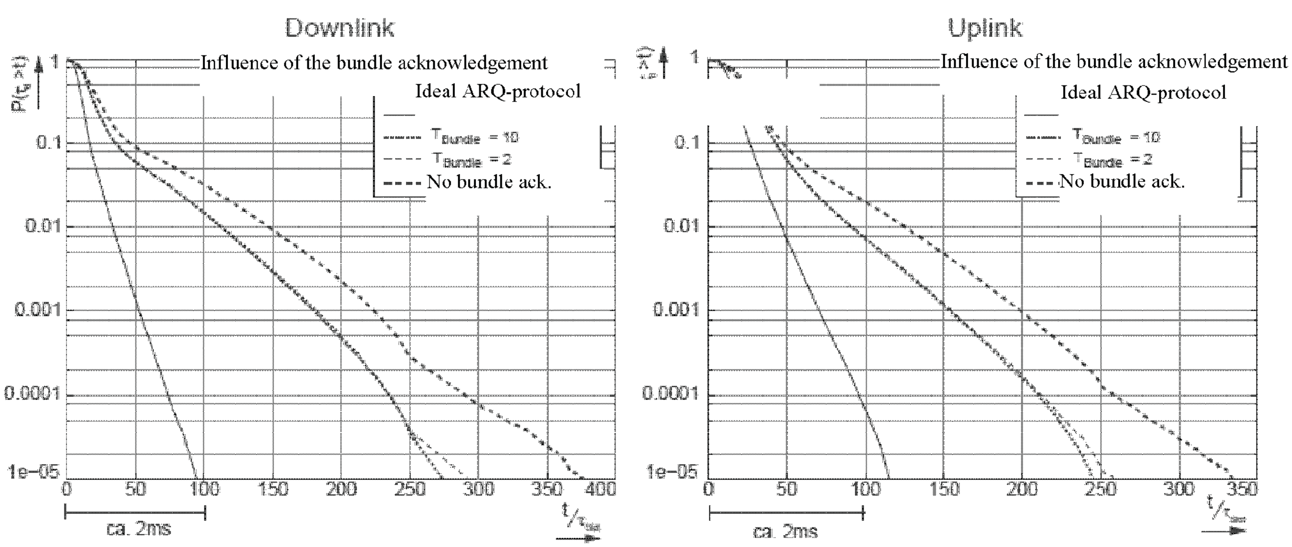


Figure 8.9: Effect of the bundle acknowledgement with uncorrelated channel errors

Figure 8.9 shows the delay of the N-PDU on uplink and downlink with uncorrelated channel errors, figure 8.10 with correlated channel errors. The simulation results show that the parameter T_{Bundle} has no influence on the delay of the N-PDU in this scenario. However, the service level requirements are better fulfilled by the usage of the bundle acknowledgement. This effect, however, is more due to the more frequent acknowledgement transfer,

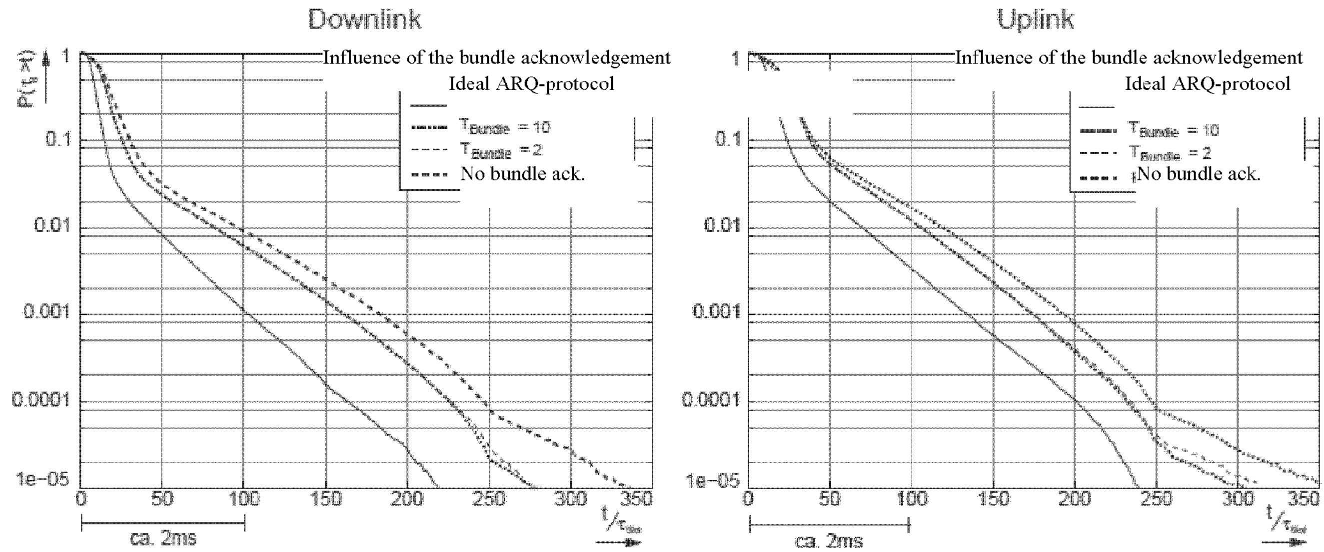


Figure 8.10: Effect of the bundle acknowledgement with correlated channel errors

because during the delivery of a bundle acknowledgement, the acknowledgements of all ARQ-instances are transferred. Here the overall delay through the bundle acknowledgement with uncorrelated channel errors is reduced even more due to the higher acknowledgement load than with correlated channel errors. For comparison, the theoretically obtainable service level with the usage of the ideal ARQ-protocol is illustrated in the figures.

8.7 Realistic simulation scenarios with multimedia services

The evaluation of the service level of real-time oriented services occurs based on two realistic multimedia scenarios with which high load cases are modeled. Their parameters are summarized in tables 8.8 and 8.9. The second scenario comes from the first one in that two 1 Mbit/s video sources are replaced with a 2 Mbit/s CBR source. This high-rate CBR connection is assigned the static VBR-priority level of the scheduler, because only low-rate CBR-connections (i.e. 64 kbit/s) are operated with the highest static priority, see section 4.1.

Service	Service class	λ	#WT	$\sum$ Last	τ_{dmax}	$\frac{\tau_{dmax}}{\tau_{slot}}$
Speech	CBR	64 kbps	4	3%	2 ms	100
Video	VBR	1 Mbps	4	44%	30 ms	1500
Data	UBR	460 kbps	4	20%	undef.	undef.

Table 8.8: Parameters of the first multimedia scenario

In table 8.10, the parameters used for the acknowledgement algorithms, the size of the ARQ-window and the maximum number of reservations are summarized. The influence on the maximum number of reservations and the influence of the ARQ-window size will be investigated further in the following. The parameters for the acknowledgement algorithms were adjusted to the scenarios based on the results from section 8.6. Other investigations are surely required here for an objective evaluation.

Service	Service class	λ	#WT	$\sum$ Last	τ_{dmax}	$\frac{\tau_{dmax}}{\tau_{slot}}$
Speech	CBR	64 kbps	4	3%	2 ms	100
ISDN-P.MUX.	VBR*	2 Mbps	1	22%	5 ms	250
Video	VBR	1 Mbps	2	22%	30 ms	1500
Data	UBR	460 kbps	4	20%	undef.	undef.

*ISDN-primary multiplex connection, only low-rate CBR-connections (i.e. 64 kbit/s) are operated by the scheduler with the highest static priority.

Table 8.9: Parameters from the second multimedia scenario

N_{ARQ}	32	$P_{T_{poll}}$	$p = 0.66$
$N_{Res\,max}$	20	$P_{T_{RACH}}$	$q = 0.5$
$N_{Ack-PCTRL\,max}$	6	T_{Bundle}	2

Table 8.10: Protocol parameter from the multimedia scenarios

8.7.1 The size of the ARQ window

The size of the ARQ-window N_{ARQ} plays a role for the delays of the ATM-cells in that only so many I-frames can be sent without being acknowledged in the meantime as the ARQ-window has memory for, see 5.2.2. This has in particular an effect on connections with burst-like arrival processes (i.e. video sources), where it is frequently possible that a whole signaling period is assigned one connection. In figure 8.11, the delays of the N-PDU are illustrated for the video sources of the first multimedia scenario. It shows that the ARQ-window should be selected larger than the maximum number of reservations $N_{Res\,max}$ (here 20), because acknowledging is first done in the next signaling period. If the ARQ-window closes within only one signaling period, the cells will be delayed unnecessarily despite adequately available channel capacity. In figure 8.11, the improvement can be clearly seen, which comes along with an expansion of the ARQ-window to 32 memory spaces. A further expansion to 64 memory spaces, in contrast, barely has any effects on the delays.

8.7.2 The maximum number of reservations

Based on the first multimedia scenario, the effects of the maximum period lengths were investigated. In the simulations, the ARQ-window of the transmitter is always selected at least twice as large as the maximum number of reservations $N_{Res\,max}$ in order to be able to fill the signaling period with burst-like arrivals as well. In figure 8.12, the effects for the low-rate CBR-connections are illustrated. For the downlink, the length of the periods is easy to recognize. The graphs bend at about $P(\tau_d > t) = 2.5\,\%$, which corresponds with the channel error and this is at the point at which the waiting time timeslots correspond with the maximum length of the reservation period. This shows that the PDUs are lost with a probability of 2.5% and need at least one more period for their transfer. A second and third disruption of the burst becomes increasingly less probably. On the uplink,

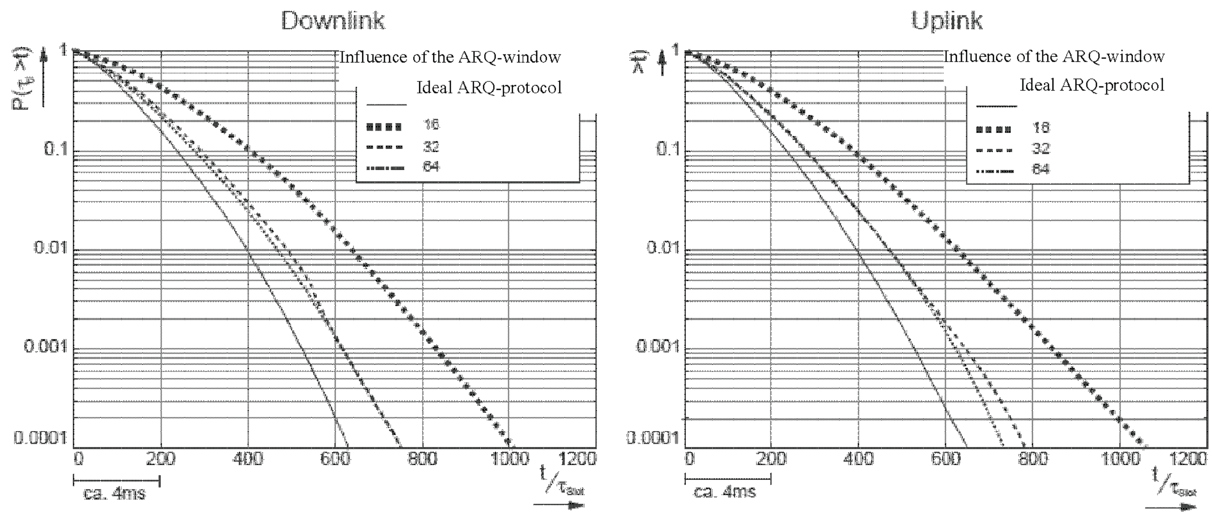


Figure 8.11: Effect of the ARQ-window size with correlated channel errors for the video connections

these effects are covered through the capacity requirements in the random access, the collisions connected with them and the collision solution. It shows that for low rate CBR-connections, short signaling periods are advantageous, because transfer repeats can be executed in a quicker manner. The additional overhead connected with short signaling periods does not hinder the CBR-connections due to their high statistical priority and their low load.

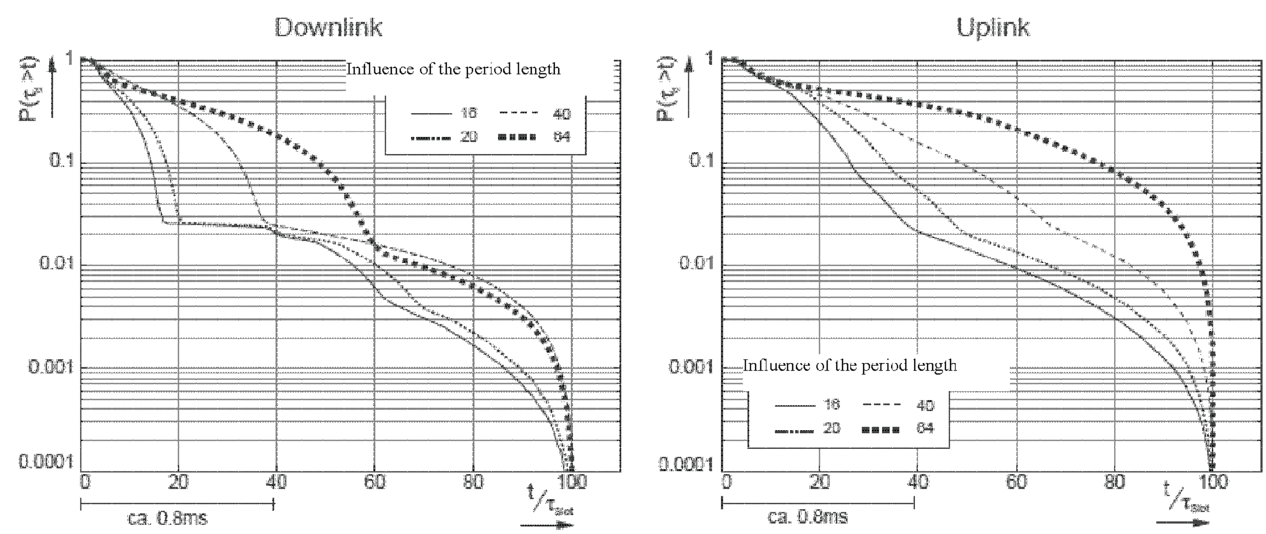


Figure 8.12: Effect of the period length by correlated channel errors for CBR-connections

The high-rate video connections profit, in contrast, profit from longer signaling periods due to their burst-like character, see figure 8.13. Thus, a period length of 64 for this special scenario leads to the smallest delays. Short signaling periods increase the dynamic of the protocol, but also the signaling effort. By the selection of the maximum period length, these two factors must be considered, moreover, the optimal selection of the parameter depends greatly on the scenario. Due to the address fields available in the PDUs for the coding of the sequence numbers, the size of the ARQ-window can be at most 32 memory spaces and

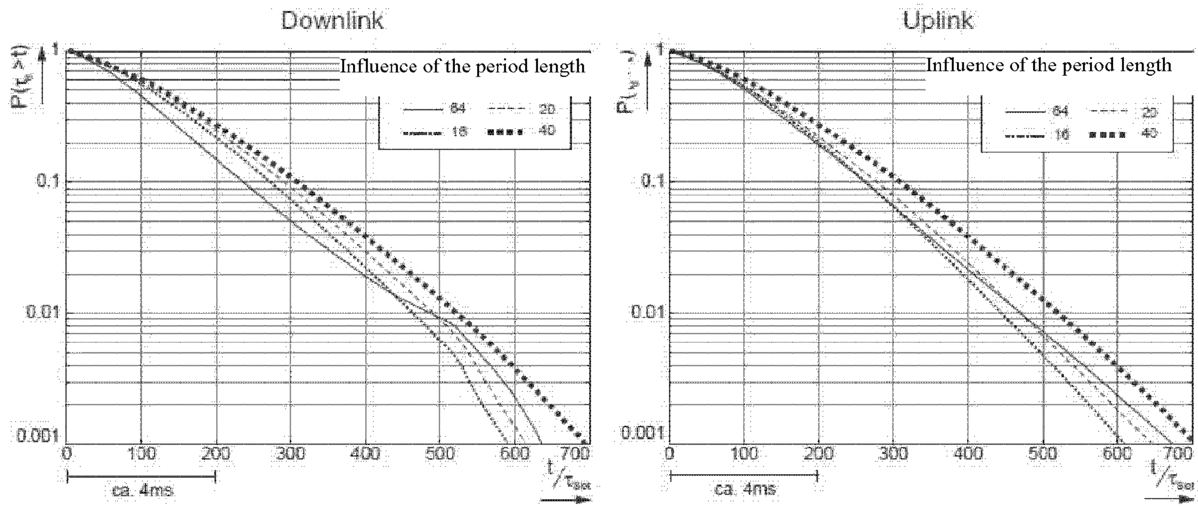


Figure 8.13: Effect of the period length with correlated channel errors for video connections

in the Period-Ctrl-PDU, a maximum of 30 reservations can be transferred, see table 4.2 and figure 4.6 Due to these basic conditions, the results from this section and the investigation in (21), $N_{Res\,max} = 20$ was selected for all other simulations.

8.7.3 Correlated and uncorrelated channel errors

In this section, the behavior of the protocol plane is compared for correlated and uncorrelated channel errors for the first multimedia scenario (see table 8.8). Since the loss of the Period-Ctrl-PDU and the disruption of the downlink burst are statistically independent for uncorrelated channel errors, the effective error rate compared to the correlated channel errors is higher, which leads to an increased load through acknowledgements and transfer repeats, see section 8.4. In figure 8.14, you will also see that the graph for uncorrelated errors bends early on the downlink than for correlated errors, for which the first bend occurs with a probability of $P(\tau_d > t) \approx 0.025$, which corresponds with the average channel error. The probability that the N-PDUs wait longer is smaller for uncorrelated errors with $t \approx 68\,\tau_{Slot}$ than for correlated ones. This means, the probability

$$P(\tau_d > 68) = \frac{1}{25} e^{-\frac{1}{25} \cdot 68} = 2.63 \cdot 10^{-3} \tag{8.3}$$

that an error burst created through the Gilbert model lasts longer than $68\,\tau_{Slot}$ is greater than the probability for the corresponding, statistically independent events, see section 7.4.2. Figure 8.14 shows that the simulated probability for $68 \cdot \tau_{Slot}$ agrees with the calculated one in the range. The probability determined through simulation is naturally larger, because shorter error bursts that occur after each other can also contribute to longer waiting times or lead to the loss of a negative acknowledgement. Table 8.11 shows the cell losses caused through schedule exceeding for the low rate CBR-connections.

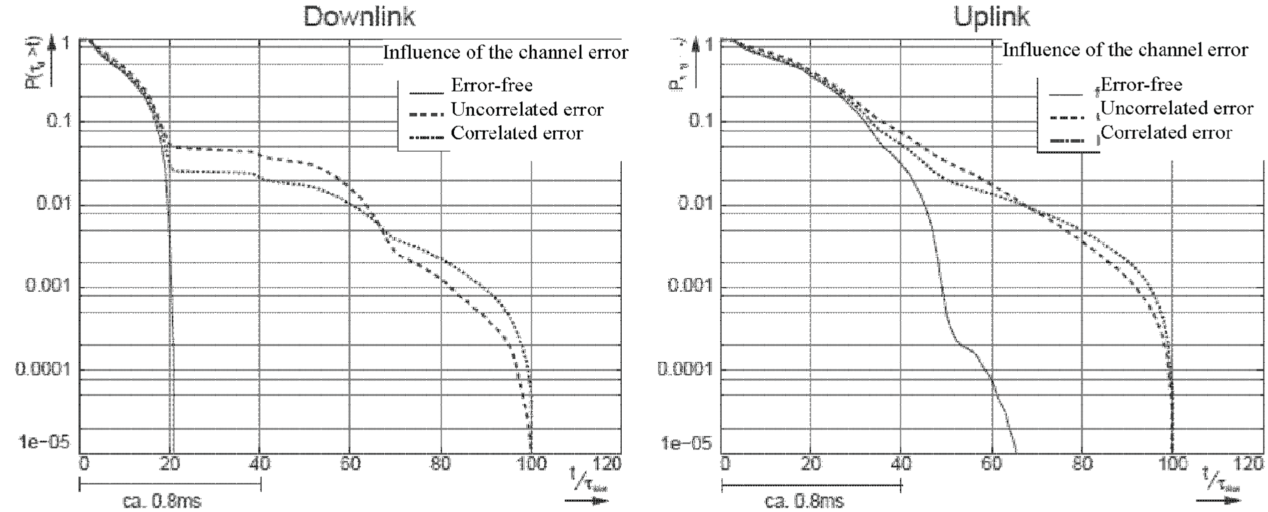


Figure 8.14: Effect of the channel error for CBR-connections

CLR	Uplink	Downlink
correlated	$2.6 \cdot 10^{-3}$	$1.01 \cdot 10^{-4}$
uncorrelated	$1.38 \cdot 10^{-4}$	0 *

*During the simulation, no cell losses occurred

Table 8.11: Cell losses due to schedule exceeding of the low rate CBR-connection

Figure 8.15 illustrates the effects of the correlated and uncorrelated channel errors on the delay for the N-PDUs of the video sources. For the downlink, characteristic bends can be seen at $t = 510\,\tau_{Slot}$. Here the requirement of acknowledgements with the help of short poll timeslots is noticeable, see section 6.2.3. The corresponding parameter $P_{T_{poll}}$was selected for this scenario at $0.66\,\tau_{d\,max}$, whereby $\tau_{d\,max}$ amounts to $1500\,\tau_{Slot}$for the video connections, see tables 8.8 and 8.10.

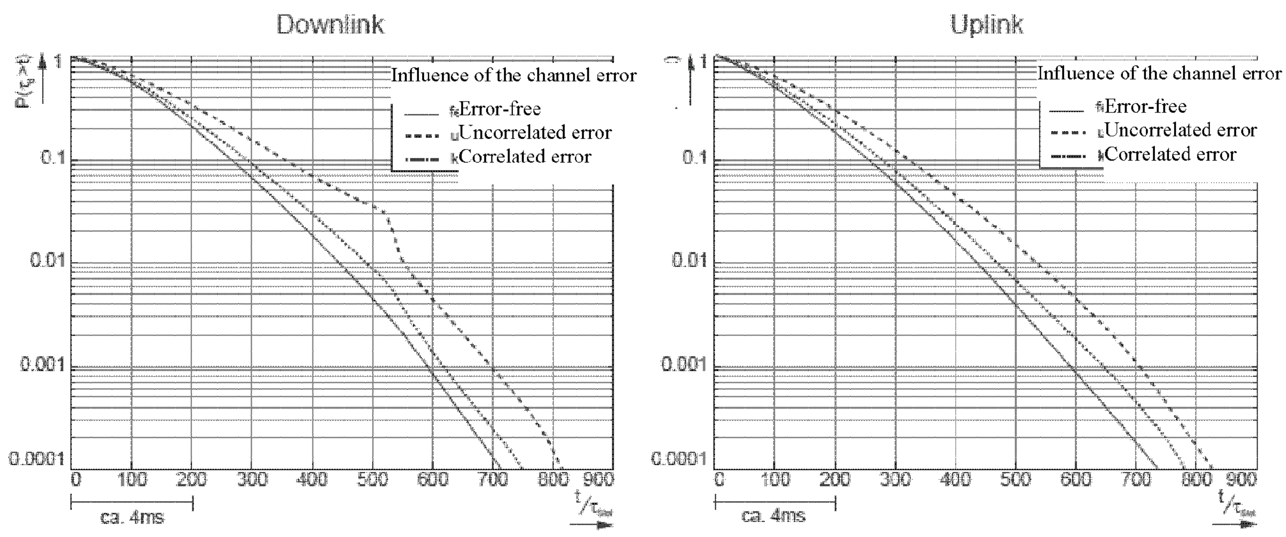


Figure 8.15: Effect of the channel error for video connections

The effects of the different error situations of the wireless channel for the high-rate

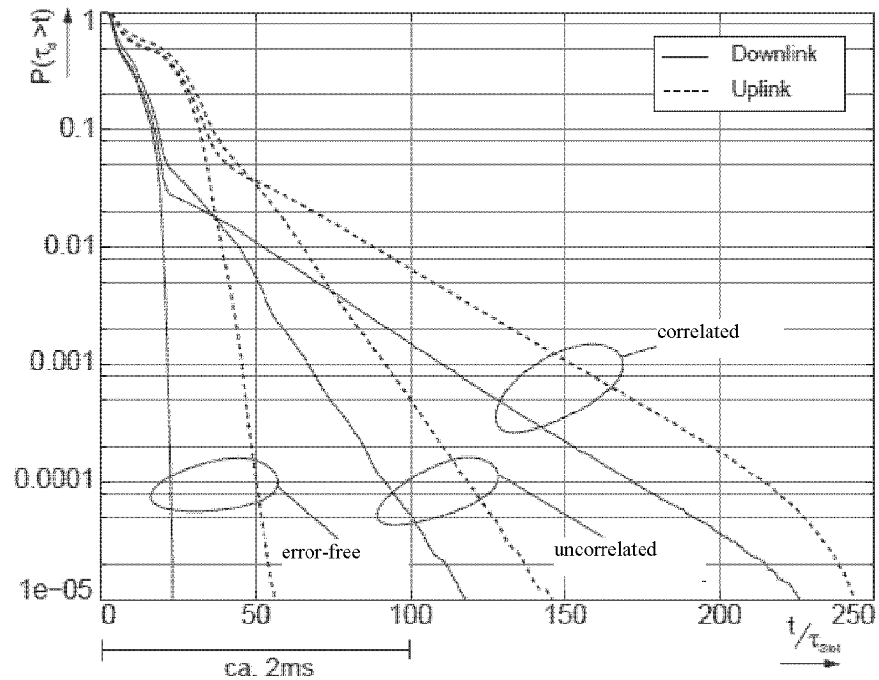


Figure 8.16: Effect of the channel error for high rate CBR-connections

	$\bar{\tau}_d$ Uplink	$\bar{\tau}_d$ Downlink
errror-free	15.853	7.350
correlated	18.253	8.596
uncorrelated	19.477	9.306

Table 8.12: Average delay of the N-PDU for uplink and downlink of the high rate CBR-connection CBR-connection of the second multimedia scenario are shown in figure 8.16 for the uplink and downlink. You can also recognize the characteristic bend by $\tau_{Slot} = 20$, which corresponds with the maximum period length in this scenario. The intervals of the delays for uplink and downlink correspond with the average length of a signaling period, because the capacity requirements of the uplink can always only be reacted to in the next period. In the linear progression of the graphs for correlated channel errors, the negative-exponentially distributed duration of the error bursts is expressed in this logarithmic illustration. With uncorrelated channel errors, there is a linear progression, here the time intervals between the statistically independent errors can also be approximated through a negative-exponential distribution. For *t* against $250\,\tau_{Slot}$, the graph for correlated channel errors bends, which is caused by the discarding of cells that have exceeded their schedule. The higher acknowledgement load with uncorrelated errors is only shown here in the upper area of the complementary distribution functions. The values for the average delay in table 8.12 show this dependency clearly.

8.7.4 The channel monitoring

The figures 8.17 to 8.19 show the influence of the channel monitoring according to section 6.4.3 on the end-to-end delay of the N-PDU for the individual service classes with correlated channel errors.

While the delays of the PDU only increase minimally through the channel monitoring for the low rate CBR connections and the high rate CBR connection of the second multimedia scenario, the clear effects on the delays of the video connections of the first multimedia scenario can be seen in figure 8.18. Through the bust-like character of the traffic of these connections, which leads to the entire signaling periods being filled with the PDUs from only one video connection, a lot of PDUs are lost in fading holes. On the one hand, this leads to an increased acknowledgement load on the channel and on the other hand, the load is increased through the many transfer repeats, which leads to longer waiting times for all PDUs from this service class. The high share of video connections in the total load of the first multimedia scenario, without the usage of channel monitoring, causes considerable losses by the service level. This results in considerable delays, from which corresponding cell losses occur due to schedule exceeding.

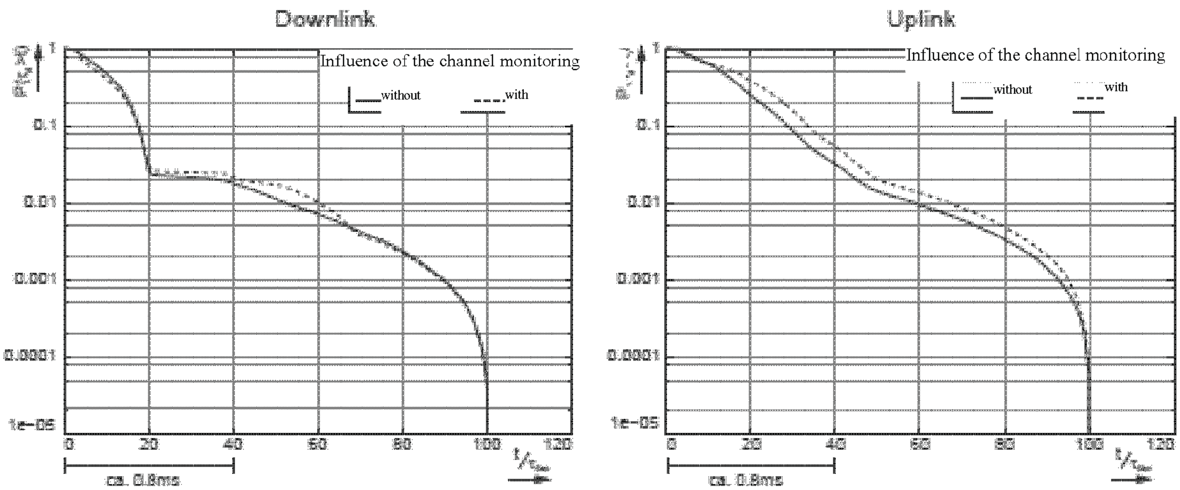


Figure 8.17: Effect of channel monitoring on the low rate CBR-connections

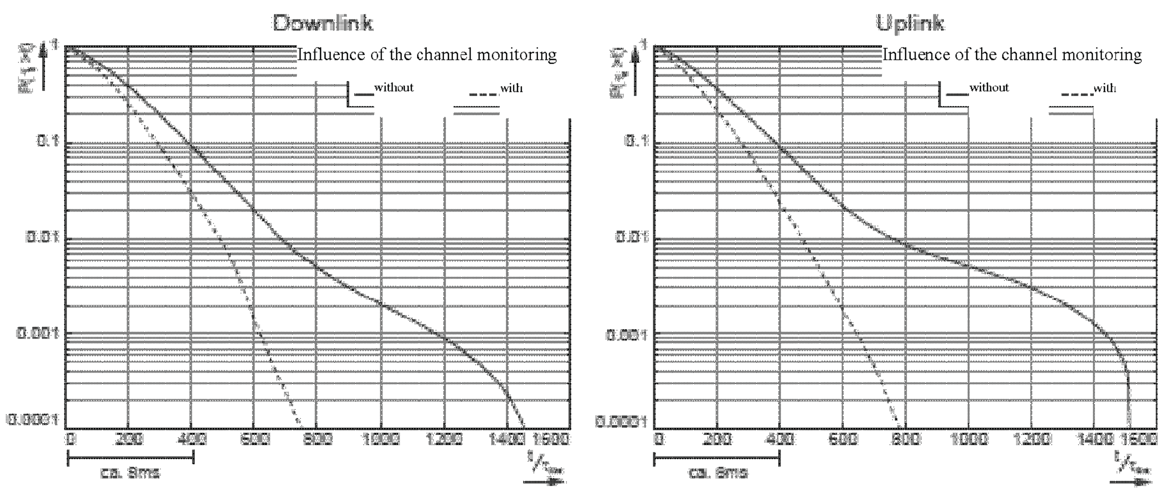


Figure 8.18: Effect of channel monitoring on the video connections

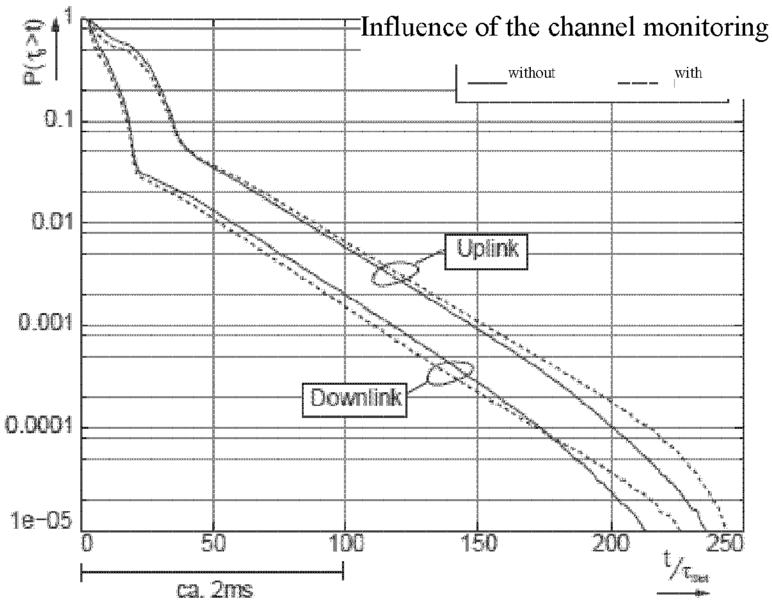


Figure 8.19: Effect of the channel monitoring on the high rate CBR connections of the second multimedia scenario

8.7.5 Comparison of the SR/D protocol with the ideal ARQ-protocol

The figures 8.20 to 8.24 compare the SR/D-protocol with the ideal ARQ-protocol for the two multimedia scenarios. The delays of the low rate CBR-connections, the high rate CBR connection and the video connections are compared for uncorrelated and correlated channel errors in order to show how far the acknowledgement strategies are from the theoretic optimal case and where there are still possibilities for optimization. By the graphs for the delays of video connections on the downlink, the characteristic bend can be seen again for uncorrelated channel errors by $510\tau_{Slot}$ again, which is caused by the threshold, which controls the insertion of short poll timeslots, see section 8.7.3.

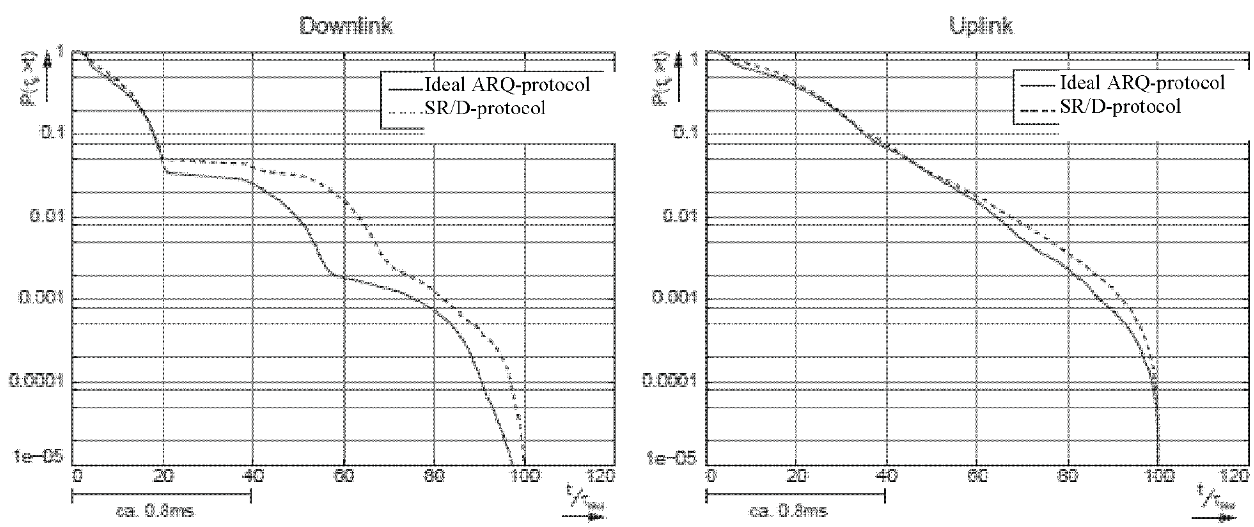


Figure 8.20: Comparison SR/D protocol for ideal ARQ for CBR connections with uncorrelated channel errors

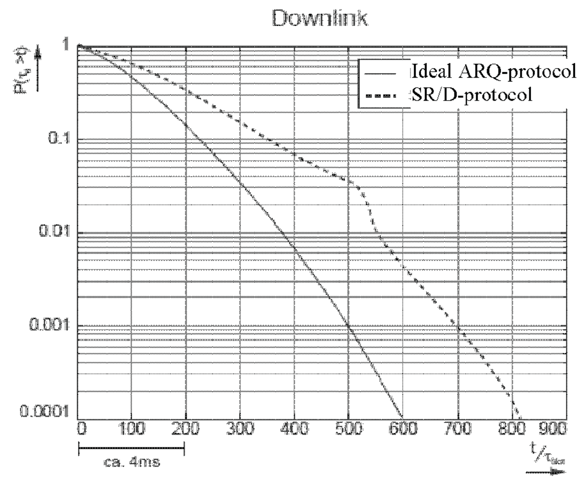


Figure 8.21: Comparison SR/D protocol for ideal ARQ for video connections with uncorrelated channel errors

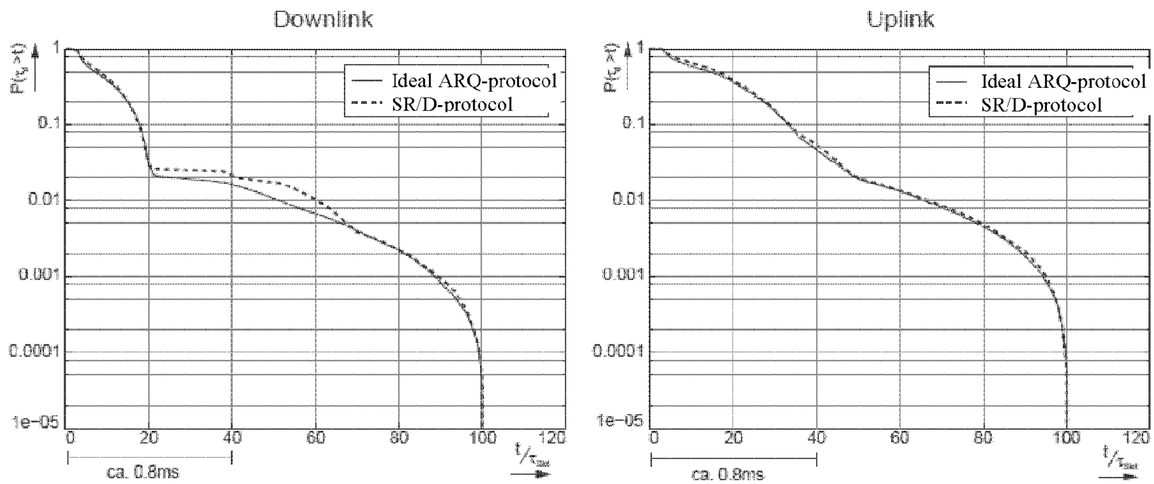


Figure 8.22: Comparison SR/D-protocol for ideal-ARQ for CBR-connections with correlated channel errors

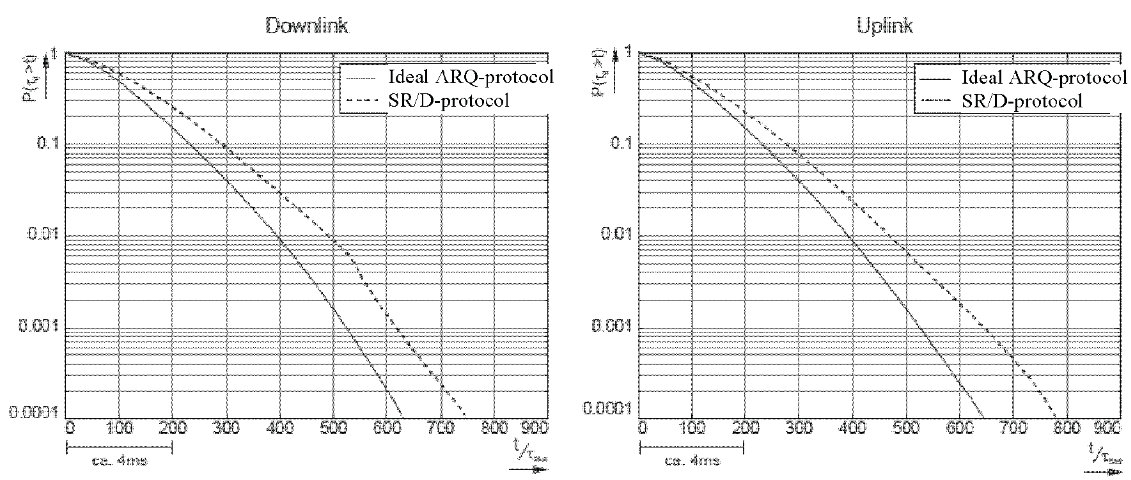


Figure 8.23: Comparison SR/D-protocol to ideal-ARQ for video connections by correlated channel errors

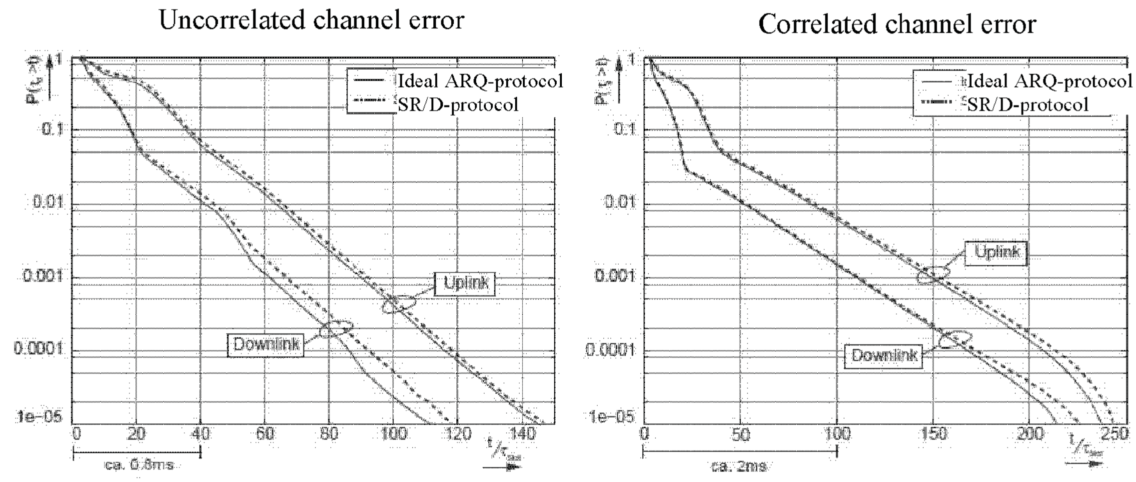


Figure 8.24: Comparison SR/D-protocol to ideal-ARQ for the high rate CBR-connection

CHAPTER 9

Summary and Outlook

9.1 Summary

The objective of this degree dissertation was the development and evaluation of service level supporting measures in a wireless based ATM-network. Through the use of service class specific ARQ protocols on the wireless interface, the punctual and efficient transfer of acknowledgements has a crucial influence on the reachability of the service levels of the individual virtual connections. Procedures were developed and implemented, which determine the priority of acknowledgements compared with information frames and which control the selection of the different methods for acknowledgement transfers.

The assignment of the available channel capacity corresponding with the requirements of the connections also has an effect on the service level. Through the burst-like transfer error s of the wireless channel, it may be that a terminal cannot receive its base station for a longer period of time. A procedure was developed to monitor the reception situation of the terminals and considered by the capacity assignment.

The ARQ-protocols (9, 36) investigated in previous works and scheduling algorithms (16) were modified for the use of the complete protocol plane and the developed procedure and the interfaces were revised. The scheduling algorithms were expanded so that the transfer of acknowledgements through the transfer sequence control is also considered for the first time.

Finally, a comprehensive performance evaluation of the procedure and the entire protocol plane was executed based on special test scenarios and with the help of realistic multimedia scenarios.

9.2 Evaluation of results

The investigations about the acknowledgement strategies showed that the punctual transfer of acknowledgements has a crucial effect on the delay of the ATM-cells. Positive acknowledgements hinder a closing of the ARQ-window, which leads to higher waiting times for the cells in the transmitter and negative acknowledgements request missing information frames again, through which the waiting times of the cells in the reception window are influenced.

- T
  he transfer of acknowledgements in the Period-Control-PDU has proven to be advantageous. Since the capacity for the acknowledgement transfer is available in this signaling PDU in the DSA++-protocol, this is a simple and efficient procedure.

- The random access due to acknowledgement transfers is not ideal for guaranteeing the required upper limit for the delays of the cells. For the acknowledgment transfer to the uplink, other procedures must be additionally used.
- In particular with a high stress of the channel (high traffic load or high load through acknowledgements and transfer repeats due to channel errors), the use of short poll timeslots for acknowledgement transfer can be advantageous.
- The bundle acknowledgement is particularly ideal if the terminals operate parallel ARQ-connections. With the help of the bundle acknowledgement, within the scope of the capacity of a long timeslot, a lot of connections can be acknowledged simultaneously.

Through the channel monitoring procedure, in particular by high burst-like traffic loads and correlated channel errors, a clear improvement of the service level could be obtained in the form of low delays and schedule exceeding ratios, because fewer information frames are lost due to transfer errors.

The performance evaluation of the complete protocol plane first showed that with the developed and implemented procedure, the transfer of ATM-cells is possible for real-time oriented services in accordance with the service level requirements with virtual connections, even with high channel stress.

Within the scope of this work, the algorithms and procedures for the transfer sequence control of acknowledgements was implemented in the simulation model, the ARQ-protocol was revised correspondingly, an ideal ARQ-protocol was developed in regards to the acknowledgement transfer, the communication between the MAC-layer and LLC-layer was expanded, the LRE-algorithm was made available for the measurements of the distribution functions and an object-oriented approach was integrated for different channel models. Thus, the important prerequisites for the differentiated performance evaluation of the complete system were created.

9.3 Outlook

During this work, a series of new questions occurred or remained open, which require further investigation:

- The performance evaluation could previously only provide a first impression of the connections. Due to the extreme dependency of the results from the scenarios and the strong mutual change effects of the individual parameters of the protocol plane, other investigations are required. In particular the behavior for parallel ARQ connections, the throughput of the protocols and the “costs” for the individual measures in the form of channel capacity must be observed in more detail.
- The information about the schedules of the ATM-cells, which are transferred in the

dynamic parameters, could be used advantageously for the priority determination of the acknowledgements.

- The integration of the protocols and scheduling algorithms for low rate CBR-services and ABR services in the transfer sequence control is still missing.

- B

  etween the service level requirements of the individual virtual connections, there should be more differentiation in the cell scheduler. For the ATM-cells, this can be realized with the help of the *Relative Urgency* strategy (16), for the acknowledgement transfer a system by which the schedule is “rewarded” for every successfully transferred cell in accordance with the service level requirements of the respective virtual connection would be imaginable (*reward system*).

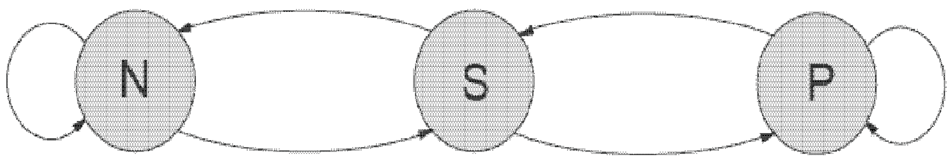


Figure 9.1: Condition transition diagram of an expanded channel monitoring

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  he procedure for channel monitoring should be expanded by a condition S (SUSPECT), because in the current implementation, there have been changes from the condition N (NORMAL) to the condition P (POLL) when the connection only reserves one timeslot and the burst of this timeslot is disrupted. This leads to the terminal not being considered in the next period even with individual uncorrelated channel errors. In the future, this should be changed to the condition SUSPECT. If all timeslots are open in this condition again (also for the case that only one was reserved), it will be moved to the POLL condition. The condition SUSPECT therefore delivers an additional support and limits the influences of random individual errors on the monitoring procedure.

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AAL	ATM Adaptation Layer
ABR	Available Bit Rate
ARQ	Automatic Repeat ReQuest
ATM	Asynchronous Transfer Mode
Ack-PDU	Acknowledge-PDU
B-ISDN	Breitband-ISDN
BSC	Base Station Controller
BST	Base Station Transceiver
BS	Base Station
CAC	Connection Admission Control
CBR	Constant Bit Rate
CDVT	Cell Delay Variation Tolerance
CDV	Cell Delay Variation
CEP	Connection End Point
CER	Cell Error Ratio
CLP	Cell Loss Priority
CLR	Cell Loss Ratio
CMR	Cell Misinsertion Rate
CNCL	Communication Networks Class Library
CPCS	Common Part Convergence Sublayer
CRC	Cyclic Redundancy Check
CS	Convergence Sublayer
CTD	Cell Transfer Delay
DCH	Data Channel
DLC	Data Link Control
ETSI	European Telecommunications Standard Institute
FCFS	First Come First Serve
FDM	Frequency Division Multiplex
FEC	Forward Error Correction
GCCH	Global Control CHannel
GFC	Generic Flow Control
GSM	Global System for Mobile Communication
HDLC	High level Data Link Control
HEC	Header Error Control
INI	Inter Network Interface
I-PDU	Information-PDU
ISDN	Integrated Services Digital Network
ITU	International Telecommunicatior Union
LLC	Logical Link Control
LRE	Limited Relative Error
L_PDU	LLC-PDU
MAC	Medium Access Control
MBS	Mobile Broadband System
MCTD	Mean Cell Transfer Delay
MS	Mobile Station
PCR	Peak Cell Rate
PCTRL	Period Control
PDU	Protocol Data Unit
PT	Payload Type
QoS	Quality of Service
RACH	Random Access
REJ	REJect
RN	Request Number
RQCH	Request Channel
RR	Receive Ready
SAP	Service Access Point
SAR	Segmentation And Reassembly
SDL	Specification and Description bf Language
SDU	Service Data Unit
SN	Sequence Number
SP	Service Primitive
SREJ	Selective REJect
SR	Selective Repeat

TCH	Traffic CHannel
TDD	Time Devision Duplex
TDMA	Time Division Multiple Access
UA	Unnumbered Acknowledgment
UBR	Unspecified Bit Rate
UNI	User Network Interface
VBR	Variable Bit Rate
VCI	Virtual Channnel Identifier
VC	Virtual Channel
VPI	Virtual Path Identifier
WT	Wireless Terminal
nt-VBR	non-real-time bf Variable Bit Rate
rt-VBR	real-time bf Variable Bit Rate

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