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MASTER

Modelling ARQ for a high-speed wireless ATM based LAN

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Master's Thesis:

Modelling ARQ
for a high-speed wireless
ATM based LAN

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Abstract

There is an increasing tendency visible in the use of the Asynchronous Transfer Mode (ATM) for broadband networks. Originally intended for the use in fixed networks, due to the increase in user mobility, large research efforts are made in investigating the use of ATM for wireless broadband networks.

In the Advanced Services and telecommunications project MEDIAN an ATM based high-speed wireless Local Area Network (LAN) at 60 GHz with a 150 Mbit/s capacity is investigated. A demonstrator has been built to show the possibilities of a wireless broadband local environment. However, the functionality of this demonstrator is still limited. To add functionality, without immediately implementing it a simulation model of a wireless LAN, based on the demonstrator, has been developed.

To ensure reliable communication, a Forward Error Correction (FEC) scheme is used leading to reasonable Cell Loss Ratios (CLR) on the wireless link. To improve the CLR, a retransmission scheme, or Automatic Repeat requested (ARQ) is proposed, to be used on top of the FEC. To enable the use of ARQ, sequence numbers are attached to the ATM cells, in order to uniquely identify each cell on the wireless link. Also, a 'Sequence Number confirmed' is added to the ATM cell to acknowledge cells going in the opposite direction. A special ACK PDU, containing a number of acknowledgements is necessary in case the traffic is unbalanced. To ensure a fast response, retransmissions are given priority over normal transmissions and requests for retransmission of cells (NACK) are given priority over the positive acknowledgements of cells (ACK).

To demonstrate the use of ARQ in the wireless LAN, a simulation model is developed using a seven stage development methodology. The model is an enhancement to the existing simulation model. The model consists of a Fixed Radio Part Controller (FRPC), two Fixed Radio Parts (FRP) and 3 Portable Radio Parts (PRP). The ARQ scheme is modelled as a state transition diagram that runs as a child process in the FRPC as well as in the PRP.

The goal of the performed simulation is to investigate the behaviour of the ARQ enhanced system for real time traffic under non error-free conditions, specifically the interaction with the used bandwidth assignment scheme. Several simulations are performed including single balanced connection, multiple balanced connections and single unbalanced connection. The main result of the simulations is that retransmissions for real-time services are achievable, leading to virtual error-free links.

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List of Abbreviations

ABR	Available Bit Rate
ACK	Acknowledgement
ACTS	Advanced Communications and Telecommunications Services
AF	Acknowledgement Field
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
CBR	Continuous Bit Rate
CDF	Cumulative Distribution Function
CDV	Cell Delay Variation
CLR	Cell Loss Ratio
CTD	Cell Transfer Delay
FEC	Forward Error Correction
FRP	Fixed Radio Part
FRPC	Fixed Radio Part Controller
ICI	Interface Control Information
ID	Identification
IF	Intermediate Frequency
IW	Inter Working
LAN	Local Area Network
LLC	Logical Link Control
MAC	Medium Access Control
MBS	Maximum Burst Size
MCR	Minimum Cell Rate
NACK	Negative Acknowledgement
NoA	Number of Acknowledgements
nrt-VBR	Non real time Variable Bit Rate
OFDM	Orthogonal Frequency Division Multiplexing
PCR	Peak Cell Rate
PDU	Protocol Data Unit
PHY	Physical
PRP	Portable Radio Part
PS	Portable Station
QoS	Quality of Service
RF	Radio Frequency
RT	ReTransmission
rt-VBR	real time Variable Bit Rate
RVCI	Radio Virtual Connection Identifier
Rx	Receive
SAP	Service Access Point
SCR	Sustainable Cell Rate
SDH	Synchronous Digital Hierarchy
SN	Sequence Number

SNc	Sequence Number confirmed
TDD	Time Division Duplex
ToE	Time of Expiry
Tx	Transmit
UBR	Unspecified Bit Rate
UTE	User Terminal Equipment
VCI	Virtual Connection Identifier
VPI	Virtual Path Identifier
WAMS	Wireless ATM Modelling Suite

1 Introduction

1.1 The wireless ATM extension

There is an increasing tendency visible in the application of the Asynchronous Transfer Mode (ATM) used for the transfer of information through networks. Initially intended for the network backbones, nowadays it is even proposed to get ATM up to the users' environment ('fibre-optic to the home'). Furthermore it may be expected that, due to the increase of user mobility, the user will demand wireless broadband connectivity in the near future.

A typical example of a broadband application where wireless connectivity would be of great value is a wireless TV studio with cameras, video and audio equipment all connected to the same wireless LAN. Another example is a surveillance system employed at a moderate factory site where a number of cameras connected are connected to a control centre. To enable recognition of faces or number plates, a link capacity of at least 4 Mbit/s per camera is required. A third example is the hospital environment where a surgeon wants to retrieve a high resolution 16 Mbit X-ray picture on his laptop computer when visiting patients.

In the Advanced Communications and Telecommunications Services (ACTS) project MEDIAN a high-speed wireless ATM based Local Area Network (LAN) is investigated [AC96]. This indoor system is specially suited for broadband wireless multimedia applications. The objective of MEDIAN is to evaluate the performance of such a system through a requirement study, analysis and simulations of parts as well as an overall simulation. The principal features of MEDIAN are:

❑   60 GHz transmission technology,

❑   Orthogonal Frequency Division Multiplexing (OFDM) scheme,

❑   Adaptive Time Division Duplex (TDD) Frame,

❑   Time of Expiry (ToE) based Medium Access Control (MAC) [Pri97],

❑   'ATM all the way' approach at 150 Mbit/s.

The principal advantage of utilising the 60 GHz frequency band is the availability of 4 to 5 GHz spectral space for all kinds of short range (< 1 mile) communications. This is the indirect consequence of the specific attenuation characteristic due to atmospheric oxygen of about 15 dB/km, which makes it unsuitable for other types of radio communication over longer (> 2 mile) distances. This abundant bandwidth resource is particularly attractive for MEDIAN like wireless access systems optimised for the support of the broadest possible range of multimedia services which in turn calls for a Quality of Service (QoS) support that, to date, can only be provided by ATM. However, information transfer according to the principles of ATM over a wireless link may easily result in a significantly degraded QoS in case no

additional measures are taken that secure the link quality. While ATM originally was designed for very high quality links with a Cell Loss Ratio (CLR) better than 10^{-9}, a wireless extension will result in a significantly higher CLR.

In the MEDIAN pilot system effective error correction measures have been implemented yielding a fair link quality. This is achieved by using a Forward Error Correction (FEC) at the physical layer, resulting in a Cell Loss Ratio (CLR) of about 10^{-8} in the downlink and 10^{-4} in the uplink. In comparison with other wireless LAN concept this is quite a good result, although it is partly due to the use of directional antennas.

For services that require a virtually error-free link, additional measures are still needed to remove the "last errors". Some form of retransmission at the expense of some transfer capacity can achieve this. The implementation of a retransmission scheme can also be seen as a measure that alleviates the signal-to-noise ratio requirements for a certain CLR to some extend, which translates in a more relaxed link budget. This is of particular significance in view of the fact that link budget is very critical at 60 GHz [Smu99], which implies that every simple measure that improves the link budget is warmly welcomed.

1.2   Project description

A wireless ATM pilot system has been developed to demonstrate high-speed communications at 60 GHz using the design parameters as previously described. This MEDIAN demonstrator consists of a Base Station (BS) and two portable stations (PS). To enable further extensions, such as user mobility, traffic management or a retransmission scheme without immediately implementing these features directly to the demonstrator, a simulation model of the wireless ATM system has been developed which already comprises the mobility concept [Meu99].

The goal of the project outlined in this thesis, is to investigate in which form a retransmission scheme can be added to the existing wireless ATM system architecture and to develop a model as an extension to the current simulation model. Due to the specific properties of the MEDIAN wireless ATM LAN it is expected that even retransmission for real-time services such as the Continuous Bit Rate (CBR) and real-time Variable Bit Rate (rt-VBR) is achievable.

With this retransmission enhanced model simulations are performed to demonstrate the system performance in terms of required buffer capacity and resulting cell ETE (End-to-End) delay with the emphasis on real-time traffic services.

1.3   Outline of this report

In this introduction a background on the development of a wireless ATM LAN at 60 GHz is illustrated and a number of possible future extensions have been listed. It reviews the project description, which is the enhancement of the current simulation model with retransmission capability.

In the first part of chapter 2 the wireless ATM LAN features that are related in some way to the development of a retransmission scheme are illustrated and the properties of the

simulation model are given. The ATM QoS and Traffic parameters are discussed. In the second part of the chapter the proposed retransmission scheme is discussed.

In chapter 3 a model of the proposed retransmission scheme is developed. This model is designed as a process model that is added to the existing simulation model. The several stages in the development process will be outlined.

Chapter 4 illustrates the use of the model. The results of several simulations performed with the model are presented.

In chapter 5 the result of the simulations will be reviewed and a number of conclusions are drawn. Also, a number of recommendations are presented with respect to further research for the wireless ATM LAN.

2   Retransmission for wireless ATM

2.1   Introduction

The previous chapter illustrated the backgrounds on the development of a high-speed wireless LAN at 60 GHz. While the wireless medium is non error-free, cell loss ratios will be significantly higher than in a fixed network, e.g. fibre-optic based networks. In these networks, the actual cell losses are often more influenced by congestion than by noise.

To improve the CLR on the wireless link, a FEC scheme is implemented in the demonstrator, using a (55,71) Reed Solomon code. Although this improves the CLR significantly it does not meet the demands of many ATM traffic types, that expect Cell Loss Ratios that are in the order of $10^{-9}...10^{-12}$. For this reason, an Automatic Repeat Request (ARQ) scheme is proposed to be used on top of the existing FEC. ARQ is chosen instead of improving the FEC codes because in general, the extra bandwidth required for ARQ is expected to be smaller. And since bandwidth is the most valuable asset in a wireless environment an ARQ scheme will be more efficient when compared to an extended FEC.

In this chapter first a model of the wireless ATM LAN is described including its typical design concepts such as the adaptive Time Division Duplex (TDD) frame structure and the Time of Expiry (ToE) based bandwidth assignment procedure. Next, a single and a multiple retransmission scheme are discussed.

2.2   WAMS

In order to evaluate further enhancements to the wireless ATM system, a simulation model has been developed. Figure 2.1 shows this Wireless ATM Modelling Suite (WAMS) that was implemented in OPNET, a comprehensive software environment for modelling, simulation and analysis of communication networks, computer systems and distributed systems. The model consists of a number of subsystems, listed in the following subsections.

2.2.1   Network part

The network part models a number of traffic sources that are connected to a 150 Mbit/s ATM stream that runs on a Synchronous Digital Hierarchy (SDH) based physical layer. Ten independent sources can be selected, either Continuous Bit Rate (CBR) or Variable Bit Rate (VBR) or a combination of both at any specified bit rate up to a total maximum of 150 Mbit/s. Each source represents a downlink connection (base station to portable station).
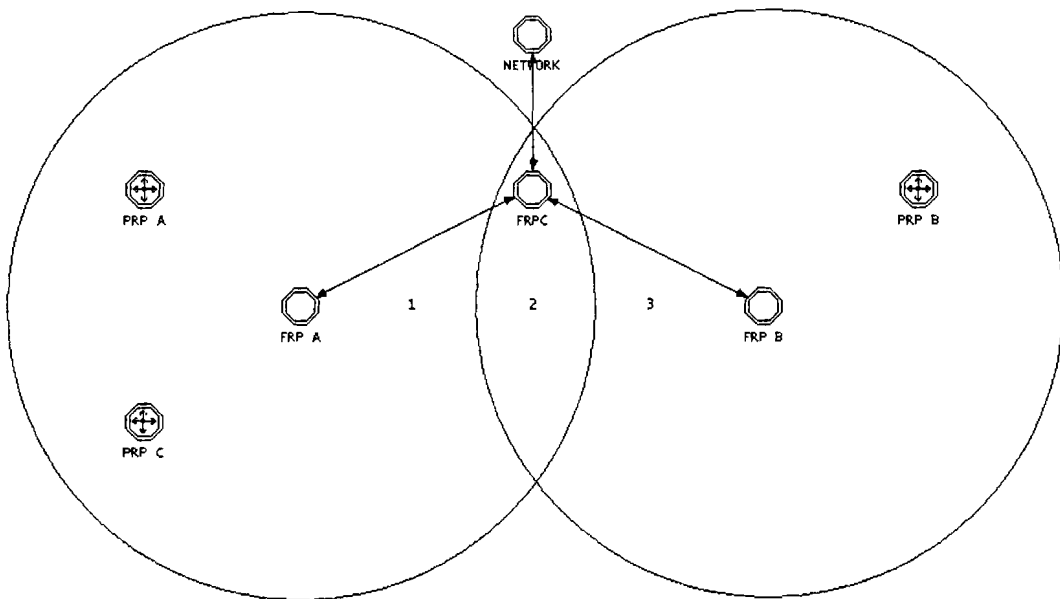
Figure 2.1: Wireless ATM Modelling Suite network model

2.2.2   Fixed Radio Part Controller

The Fixed Radio Part Controller (FRPC) is the heart of the system and adapts the fixed part of the network to the radio part. It comprehends functionality of the MAC subsystems and InterWorking (IW) subsystems. It is divided in 3 parts

❑   The Logical Link Control (LLC) layer contains the IW functions. It controls all logical links (hence the name) and assigns a link ID to uniquely identify each connection in progress. The link ID is a short representation of the ATM VCI/VPI concept. The LLC uses a Link Resource Table to store link based information such as the relation between VCI/VPI and link ID, and the type of link (e.g. user, signalling). The Semi Permanent Table stores the parameters of the links, $\Delta_{max,up}$, $\Delta_{max, down}$ and the FRP that is associated in relation to the RVCI (these concepts are explained later). The LLC layer handles all signalling and management cells.

❑   The Medium Access Control (MAC) layer is responsible for the task of assigning bandwidth to the uplink and downlink connections by calculating the broadcast cell using the frame structure and the Time of Expiry (ToE) principle, discussed in the next sections. To identify a link it uses the concept of the Radio Virtual Connection Identifier (RVCI). The distinction between RVCI and link ID is necessary because there may be more than one RVCI associated with the same connection, for instance during a handover.

❑   The physical (PHY) layer has no other functionality than to interact directly with the Fixed Radio Part.
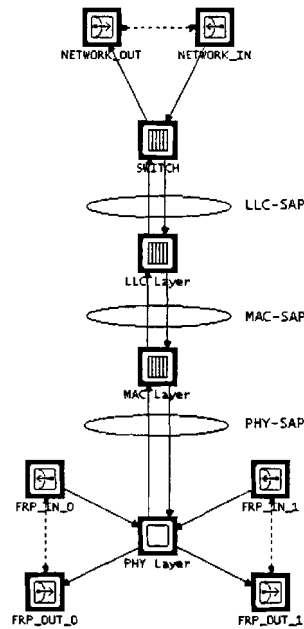
Figure 2.2: Fixed Radio Part Controller (FRPC)

2.2.3   Fixed Radio Part

The Fixed Radio Part (FRP) comprises radio-related functions: baseband subsystem, RF/IF radio subsystem and antenna subsystem. It transmits the downlink subframes and receives the uplink subframes. The two FRPs in the model each serve their own region (cell) and are controlled by the FRPC.
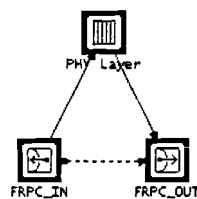
Figure 2.3: Fixed Radio Part (FRP)

2.2.4   Portable Radio Part

The Portable Radio Part (PRP) together with User Terminal Equipment (UTE) comprises the Portable Station (PS). The UTE represents a portable user device, such as a laptop computer, Personal Digital Assistant (PDA) or any other multimedia device whereas the PRP acts as the wireless extension of the PS. Like the FRPC, it is divided into a LLC, MAC, and PHY layer:

❑ The PRP LLC layer has the same functionality as its FRPC counterpart. It contains the
   IW functions, controls all logical links and maintains the link IDs in the Link Resource
   Table.

❑ The PRP MAC layer is somewhat different as the FRPC MAC layer. While the latter
   assigns bandwidth by calculating the broadcast cell, the PRP MAC layer acts as a slave to
   the FRPC MAC layer. It interprets the Broadcast Cell and uses the information contained
   in it to inform the physical layer when to receive and when to transmit. It informs its peer
   entity of the number of cells waiting in the buffer separately for each RVCI. The FRPC
   MAC uses this information to allocate and divide the bandwidth to the connections in
   progress.

❑ The PRP PHY layer comprehends radio-related functions: baseband subsystem, RF/IF
   radio subsystem and antenna subsystem. It transmits in the uplink subframe in the slots
   assigned to it and receives the assigned slots from the downlink subframe.
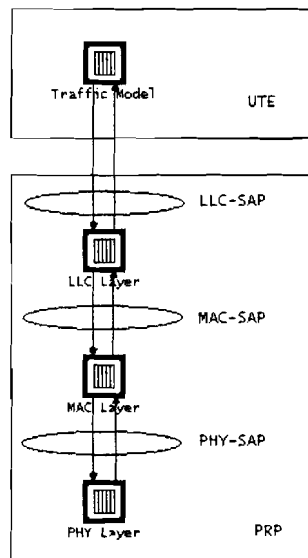
Figure 2.4: Portable Radio Part (PRP)

2.2.5   WAMS timing

The total delay that any cell belonging to a certain connection encounters for the wireless link
must comply with the ATM Cell Transfer Delay (CTD) parameter as established during the
connection set-up. Figure 2.5 shows the base station (FRPC and FRP) and the portable station
and the several delays.

The delays are modelled ate the Service Access Points (SAP) and are 'experienced' by a cell
when it is transferred from one layer to another layer.

The maximum delay for the wireless link as part of the total CTD is hereafter denoted as 'link
CTD'. In addition Δ_{max} is introduced as the link CTD minus the fixed processing delays in
several parts of the system:

$$\Delta_{max} = link\ CTD - 2\ (\Delta_{MAC\text{-}SAP} + \Delta_{PHY\text{-}SAP}) - \Delta_{LLC\text{-}SAP} - \Delta_{propagation}$$
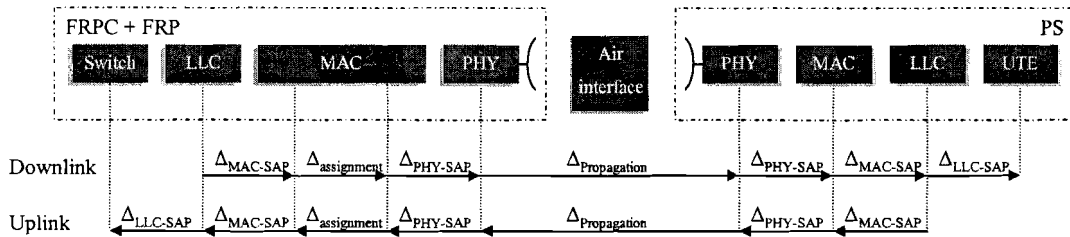
Figure 2.5: WAMS timing

The Δ_{max} parameter represents the maximum time any cell belonging to a certain connection may wait in any queue present in the system. In practice this reflects mostly on the time cells wait in the MAC queue in order to be scheduled. In fact, Δ_{max} is the basis of the ToE principle used in the MAC in order to schedule the cells. The fixed delays are defined at the various Service Access Points and are based on experiences with the MEDIAN demonstrator. From the 'ARQ' point of view the total variable delay is more important than the fixed delay as this gives room to do any retransmissions.

2.3   Adaptive TDD

The system and the derived model make use of an adaptive Time Division Duplex (TDD) frame structure shown in Figure 2.6. A frame consists of 64 slots of 2.667 µs, hence the frame duration is 170 µs. The number of slots that is granted to the downlink and uplink is determined on a frame by frame basis by the scheduler entity in the FRPC MAC layer and depends on the number of cells waiting in the base station and an estimation on the number of cells waiting in the portable stations. The broadcast cell informs the portable stations of the slot assignments. However, to facilitate processing by the portable stations, the slot assignments in the broadcast cell of frame (n) refer to frame ($n+2$). The reference symbol is used for frame synchronisation by the physical layer. The available slot is used by portable stations that intent to set up a connection. The unused slots are used for Rx/Tx switching and the empty slots are slots that are left unassigned to any connection.

Downlink subframe	Slot 1	REFERENCE SYMBOL
	2	BROADCAST CELL
	3	USER SLOT TO PRP
	4	USER SLOT TO PRP
	⋮	
	m	USER SLOT TO PRP
	m + 1	UNUSED SLOT
Uplink subframe	m + 2	USER SLOT FROM PRP
	⋮	
	n	USER SLOT FROM PRP
	n + 1	EMPTY SLOT
	⋮	
	62	EMPTY SLOT
	63	AVAILABLE SLOT
	64	UNUSED SLOT
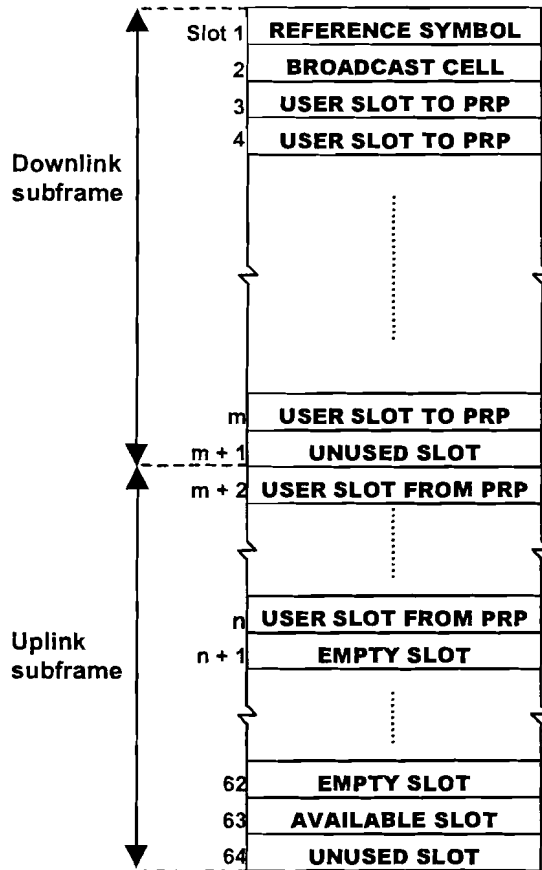
Figure 2.6: Adaptive TDD frame structure

2.4   ToE and polling concept

The scheduling of cells is executed by the FRPC MAC layer, using the Time of Expiry principle [Pri97]. For the downlink part of the connection, the MAC scheduler assigns each arriving cell a time, t_{max}, that indicates the maximum time before that cell has to be transmitted over the air. It is determined by using the connection parameters established during the connection set-up phase:

$$t_{max,down} = t_{arr} + \Delta_{max, down} (c)$$

In this formula, t_{arr} indicates the arrival time of the cell in the FRPC and $\Delta_{max,down}$, (c) is the maximum delay time any cell of the connection c may encounter in the wireless part of the network.

For the uplink connections the calculation is somewhat different because the FRPC has no knowledge of cell arrival times in the PRP. Therefore it has to calculate the $t_{max, up}$ by using the arrival time at the FRPC of the previous cell, say the $(j-1)^{th}$ one, of the connection c:

$$t_{max, up} = t_{arr}(c, j-1) + \Delta_{max, up}(c)$$

The parameter $M(c,t)$ is used to predict the number of cells of the connection c the scheduler presumes to be waiting at time t in the PRP MAC buffer without having yet obtained a slot assignment. Every uplink MAC PDU has an information field, indicating how many cells are waiting in the PRP MAC buffer at the moment of transmission of the cell. The MAC scheduler calculates how many new uplink cells have arrived since the reception of the $(j-1)^{th}$ one as the difference between the information derived from the arrived MAC PDU and the just retrieved parameter $M(c,t)$. This difference, denoted as $N(c,t)$, indicates for how many cells the parameter t_{max}, up is valid. Hereinafter the parameter $M(c,t)$ is set to the contents of the MAC PDU information field.

If an uplink connection remains idle for a certain period, the PRP has no way of informing the FRPC of any cells waiting in the MAC buffer. A polling mechanism is used to give PRPs a periodical opportunity to transmit an uplink cell and inform the FRPC MAC scheduler of its buffer contents. The time of expiry for such a polling record is:

$$t_{max, polling} = t_{arr}(c, j-1) + \Delta_{polling}(c)$$

With $\Delta_{polling}$ being a static parameter established during the connection set-up. To decrease the overhead $\Delta_{polling}(c)$ is often chosen significantly larger than $\Delta_{max, up}(c)$.

For each frame, the scheduler now calculates the number of slots it assigns to the uplink and to the downlink on the basis of the number of cells waiting in the FRPC MAC buffers, their $t_{max, down}$ and on an estimation of the number of cells waiting in the PRP MAC buffers and the $t_{max, up}$.

2.5 ATM QoS and Traffic parameters

In order to categorise the traffic the ATM Traffic Management Specification [ATM96] distinguishes 5 ATM service classes each with their own set of parameters to describe the sort of traffic offered to the network and the QoS which is required from the network. The five service classes are:

❑ Continuous Bit Rate (CBR)

❑ Real time Variable Bit Rate (rt-VBR)

❑ Non real time Variable Bit Rate (nrt-VBR)

❑ Unspecified Bit Rate (UBR)

❑ Available Bit Rate (ABR)

Each of these service classes is characterised by a set of QoS parameters and traffic parameters. The QoS parameters are:

❑ Cell Loss Ratio (CLR)

❑ Cell Transfer Delay (CTD)

❑ Cell Delay Variation (CDV)

The CDV is an upper bound on the variability in the pattern of cell arrivals observed at a single measurement point with reference to the peak cell rate. The CLR is the number of lost ATM cells in proportion to the total number of cells for a connection. The CTD is the maximum delay any ATM cell may encounter from source to destination.

The traffic parameters are:

☐   Peak Cell Rate (PCR)

☐   Sustainable Cell Rate (SCR)

☐   Maximum Burst Size (MBS)

☐   Minimum Cell Rate (MCR)

The PCR is an upper bound on the traffic that can be submitted on an ATM connection. The SCR is an upper bound on the average rate of an ATM connection, calculated over the duration of the connection.

The ATM QoS parameters, particularly the maximum Cell Transfer Delay (CTD), are the basis to decide whether or not to perform a retransmission. Table 2.1 gives an overview of the ATM service classes and related traffic- and QoS parameters:

	CBR	rt-VBR	nrt-VBR	UBR	ABR
Traffic parameters	PCR	PCR, SCR, MBS	PCR, SCR, MBS	PCR (optional)	PCR, MCR
QoS parameters	CTD, CLR, CDV	CTD, CDV, CLR	CLR	-	-

Table 2.1: ATM Service classes and related QoS and traffic parameters

2.6   ARQ

The ARQ scheme discussed in this section is partly based on the ARQ scheme proposed in [Ber98] and is especially designed to allow retransmissions for real-time services, like the Continuous Bit Rate service and the real-time Variable Bit Rate service. The protocol chosen should meet the stringent delay requirements that are typical for real-time services. Also, it should not require significant overhead in terms of transfer capacity. In general, to enable the use of an ARQ scheme for such real-time services in radio-based networks, the system needs to meet the following conditions:

☐   Sufficient storage capacity at both the transmitting and receiving end

☐   Detection of cell losses

☐   Identification of the lost cells and notification to the transmitter

☐   Adequate scheduling algorithm to react fast on requests for retransmissions

☐   Priority of retransmissions over new transmissions

❑ Available capacity for sending retransmissions

Basically, there are three ways to implement ARQ [Sta95]. Stop-and-Wait, Go-Back-n and Selective Repeat (SR). The Stop-and-Wait protocol sends a cell to the receiving end and then waits before sending the next cell until the current one is acknowledged. It is immediately clear that this will increase the overall cell delay and the buffer capacity at the transmitting end. Go-Back-n allows a maximum of n outstanding cells, hence a maximum of n cells can be transmitted before the first cell needs to be confirmed. Although this protocol improves the cell delay and the need for buffer capacity is less, it still requires a considerable extra capacity on the wireless link. Another drawback is that, while a group of cells is retransmitted the probability that there is an error in the group of cells is higher as compared to the retransmission of a single cell. This is the reason why SR is the most efficient protocol for wireless networks and therefore it is chosen as the basis for the proposed ARQ scheme.

Now that the selective repeat protocol is chosen as the most efficient for wireless networks it needs to be determined how to enhance the existing model with retransmission capability without altering the fundamental concepts such as the frame structure and the ToE principle. First the LLC Protocol Data Units are introduced, next two retransmission schemes are introduced, one for single and one for multiple retransmissions. Also the required storage capacity and priority mechanisms are reviewed.

2.6.1 The LLC PDU

The LLC Protocol Data Unit (PDU) is introduced to enable the exchange of cell related control information at the LLC level. In the LLC DATA PDU, a header is attached to the user ATM cells. In this LLC DATA PDU header a number of fields are used to add control information, related to the user ATM cell. Wireless Specific LLC PDUs are used to exchange information for management and control, e.g. handover control.

2.6.1.1 LLC DATA PDU

To uniquely identify each cell on the wireless link, sequence numbers (SN) are included in the LLC PDU header. For the acknowledgement of cells belonging to the opposite direction, the LLC PDU header also incorporates a 'Sequence Number confirmed' (SNc) field and a 'SNc status' field. The 'SNc field' contains a SN of a cell of the same connection (link ID) in the opposite direction, the 'SNc status' field contains an acknowledgement for that cell. The value of this field can either be 'ACK' or 'NACK', depending whether the cell was received correctly or incorrectly, respectively. Figure 2.7 shows the resulting LLC DATA PDU. The TYPE field separates the DATA PDU from other LLC PDUs such as the LLC ACK PDU and future enhancements.

TYPE	SN	SNc	SNc status	ATM cell (payload)
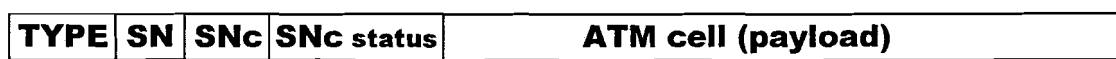
Figure 2.7: LLC DATA PDU

2.6.1.2 ACK PDU

Confirming cells of the downlink direction by attaching their sequence numbers to a cell of the uplink direction and vice versa is referred to as 'piggybacking'. However, this will not be possible if the traffic of a connection is unbalanced, that is, if one direction has a higher bit rate than the opposite one. In such cases cells have to be confirmed by using special acknowledgement cells, named 'ACK PDUs' as shown in Figure 2.8.

TYPE	NoA	AF

Figure 2.8: LLC ACK PDU

The Number of Acknowledgements (NoA) field determines how many cells are confirmed, that is, how many sequence numbers and related status there are in the Acknowledgement field (AF).

The maximum number of sequence numbers in the AF field depends on the length chosen for the sequence numbers which, in turn, depends on the number of outstanding sequence numbers in the wireless link. Simulations are needed to determine the sequence number length.

2.6.2   Single retransmission scheme

The single retransmission scheme allows for cells to be retransmitted only once. If a retransmission gets lost the cell is discarded. This will simplify the identification of lost cells at the receiver as can be seen in the example illustrated in Figure 2.9.
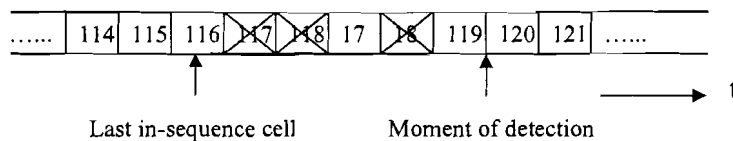
Figure 2.9: Example of the detection of erroneous cells

Cell 117, 118 and retransmitted cell 18 are lost. Retransmitted cell 17 is received correctly and is identified as a retransmission because its sequence number is lower than the using the '*last in-sequence cell*' which was stored in memory (cell 116). At the moment cell 119 arrives it is determined if any previous cells are lost by using the '*last in-sequence cell*' again. The number of lost in-sequence cells is deducted as the '*last in-sequence*' cell minus the current cell minus one, in our example:

'Number of lost in-sequence cells' $= 119 - 116 - 1 = 2$

The sequence numbers of the lost cells are identified by adding 1 to the '*last in-sequence cell*' until the number of lost cells is reached:

$$SN_1 = 116 + 1 = 117$$
$$SN_2 = 116 + 2 = 118$$

The retransmitted cell 18 is simply ignored and hence it is discarded. The Last in-sequence cell is now set to 119.

2.6.3   Multiple Retransmission scheme

To allow multiple retransmissions, the receiver has to keep track of the retransmitted cells by storing their sequence numbers in a queue. Also, a *'number of lost cells'* parameter is kept. Now refer again to the same example in Figure 2.9. When cell 119 arrives, the *'number of lost cells'* parameter reads 3 (117, 118, 18). The *'last in-sequence cell'* is 116. Now the following parameters are deducted. The *'Number of lost in-sequence cells'* is calculated the same as in the single retransmission example and the *'Number of lost retransmissions'* is calculated as the *'Number of lost in-sequence cells'* minus the *'Number of lost cells'*. In the example shown this results in:

$$\text{'Number of lost in-sequence cells'} = 119 - 116 - 1 = 2$$
$$\text{'Number of lost retransmissions'} = 3 - 2 = 1$$

The sequence numbers of the lost in-sequence cells are identified in the same way as in the single retransmission scheme:

$$SN_1 = 116 + 1 = 117$$
$$SN_2 = 116 + 2 = 118$$

The sequence number of the retransmitted cell is determined by looking at the element on top of the queue that stores the sequence numbers of the cells that are expected to be retransmitted. Assumed is that this element is the sequence number of the cell that was acknowledged to the peer entity the longest time ago and hence was retransmitted first. The retransmission of cells should therefore always occur in the order they were (negatively) acknowledged.

2.6.4   Buffer capacity

To enable a retransmission of a cell, it should be stored at the transmitter until it is acknowledged positively or until a timer that has been set for the cell expires. The capacity of the buffer that is needed is determined by the time it takes a cell to be confirmed to the transmitter. This time depends on a number of parameters:

❑   The CLR of the wireless link

❑   The roundtrip delay time of the system

❑   The uplink/downlink ratio of the connection

At the receiving end a buffer is needed to store the cells *(n+1........n+k)* that arrive just after cells *(n-m-1....n)* were lost until those specific cells are retransmitted and arrive without error at the receiver, or until a timer that was set for cells *(n+1.......n+k)* expires. The parameter *k*

is the number of cells that arrive without error before another cell $(k+1)$ is lost, and m is the number of succeeding lost cells.

2.6.5   Priority

To accelerate the ARQ scheme retransmission process, cells that are retransmitted should have a priority over the normal transmissions. Also, negative acknowledgements should have a priority over positive acknowledgements in order to inform the transmitter as soon as possible that a retransmission is required.

2.6.6   ARQ functional entities

Although the single retransmission scheme is easier to implement, and it may be expected that the majority of retransmitted cells will only undergo one retransmission, to perform simulations, a multiple retransmission scheme is chosen because this scheme will also show how a single retransmission scheme would have performed. In first instance however, an error free return link will be assumed.

The most suitable part of the system to implement the ARQ scheme is the LLC layer of the Fixed Radio Part Controller as well as the LLC layer of the Portable Radio Part. The FRPC part and the PRP part of the ARQ scheme will basically have the same functionality, so only the base station ARQ architecture is shown in Figure 2.10. In this Figure, the cell flow is shown with bold arrows, processes are depicted as ellipses whereas buffers and tables are represented as rectangles. The following subsections deal with the ARQ architecture processing blocks and relevant buffers and tables. For each connection, at LLC level identified by its link_ID, separate buffers and tables are kept.

Figure 2.10: FRPC ARQ architecture

2.6.6.1 Downlink controller

The Downlink controller has three tasks:

❑   Upon arrival of an ATM cell the Downlink controller stores the cell in the Downlink buffer and forwards a copy of the cell to the MAC layer. A timer is set to indicate the expiry time of the cell, based on the link CTD that was determined during the connection set-up for the wireless extension link for which the parameters $(\Delta_{max,\ down}$ and $\Delta_{max,\ up})$ are stored in the semi-permanent table. The timestamp, indicating the moment of arrival in the LLC layer, as well as the link_ID that was extracted from the Link resource table, are handed over to the MAC layer.

❑   When an uplink cell arrives, the ACK/NACK detection process extracts the SNc and SNc status. The Downlink controller looks the cell with the SNc up in the Downlink buffer and forwards a copy of the cell to the MAC if the SNc status is equal to 'NACK' or it removes the cell from the buffer if the field is equal to 'ACK'

❑   If a timeout occurs the cell for which the timer was set is removed from the Downlink buffer

2.6.6.2 Header attacher

The header attacher encapsulates the arriving ATM cell into a LLC DATA PDU and sets the SN field to the value it extracts from the SN counter after which this counter is incremented. Just before sending any cell to the MAC layer a SNc with its SNc status is appended.

For a cell that is a retransmission a SNc with SNc status = ACK will always be used. This is because the priority mechanism might privilege this cell before normal cells in which case the order of retransmission as received by the FRPC might be changed which will corrupt the detection mechanism if such a retransmission is lost.

For a normal cell the Header attatcher will first look for a SNc with SNc status = NACK in the SNc table in order to have the other end send any retransmissions as soon as possible. If such a SNc is not available it will append the element at the head of the SNc table (the oldest SNc in the SNc table).

2.6.6.3 Uplink controller

The Uplink controller has two more or less separate tasks: It processes the cells handed over by the Lost PDU detection entity and it responds to the timeouts for cells from the Uplink timeout table. In the first case it depends on the status of the Uplink buffer and the status of the Exp. RT table how a cell is handled. There are four possibilities, shown in Table 2.2.

Cell	Uplink Buffer status	Exp. RT status	Action
In-sequence	Not empty	Not empty	Append cell at tail of Uplink buffer
In-sequence	Empty	Not empty	Append cell at head of Uplink buffer
In-sequence	Empty	Empty	Send the cell directly to the switch
Retransmission	Not empty	Not empty	Depends on SN

Table 2.2: Cell handling by the FRPC Uplink Controller

The case when a retransmission arrives and the Uplink buffer and the Exp. RT table are not empty is illustrated in the following example:

Exp. RT table	
Pos.	SN
1	10
2	11
3	16
4	17
5	18
6	22

FRPC Uplink Buffer	
Pos.	Cell
1	12
2	13
3	14
4	15
5	19
6	20
7	21
8	23
9	24

Figure 2.11: FRPC uplink buffer

❑ If the cell with sequence number 10 arrives it will be transmitted to the switch and removed from the Exp. RT table.

❑ If the cell with sequence number 11 arrives it will be inserted at position 1 and a timeout timer will be set. The timeout timer for cell 12 will be stopped.

❑ If the cell with sequence number 16 arrives it will be inserted at position 5.

❑ If the cell with sequence number 17 arrives it will be inserted at position 5 and a timeout timer will be set.

❑ If the cell with sequence number 18 arrives it will be inserted at position 5 and a timeout timer will be set. The timeout timer for cell 19 will be stopped.

❑ If the cell with sequence number 22 arrives it will be inserted at position 8.

❏ If the cell with sequence number 25 arrives it will be inserted at the tail of the buffer, currently position 10.

If a timeout occurs it will always be the timeout that was set for the cell at the head of the buffer. All cells from position *(1...n)* with *SN(n+1)* > *SN(n)* + *1* will be send to the switch. The cells in the Exp. RT table where the cell at position 1 was waiting on will be set to 'EXPIRED'. They are not removed because if such a cell would still be received it would not be possible to identify it.

2.6.6.4 Lost PDU detection

The lost PDU detection process entity will determine if a cell is received correctly on the basis of receive status handed over by the MAC. The lost PDU counter is incremented if the Receive status = 'FAIL'. If the Receive Status = 'SUCCES' The process determines if it is a retransmission or an in-sequence cell on the basis of the value of the 'Last in-sequence cell received' parameter. In the first case the Exp. RT table is updated and the cell and related parameters are handed over to the uplink controller. In the latter case, depending on the value of the Lost PDU counter, the identification of lost cells is executed as described in section 2.7.3. Then the SNc table and the Exp. RT table are updated and finally the last in-sequence cell parameter is updated, and the Lost PDU counter is reset.

2.6.6.5 ACK PDU generator

In case of an unbalanced connection the FRPC can not piggyback all acknowledgements for uplink cells to its downlink cells. Instead, it has to send acknowledgements for cells from the uplink direction in a LLC ACK PDU. The ACK PDU generator generates such an ACK PDU on the basis of:

❏ The number of sequence numbers in the SNc table with a positive acknowledgement

❏ The number of sequence numbers in the SNc table with a negative acknowledgement

❏ The number of sequence numbers that can be contained in the AF field.

The first factor is important because these cells need to be transmitted as soon as possible. The second factor is important to limit the size of the PRP uplink buffer. The third factor is determined by the actual length chosen for the sequence numbers.

2.6.6.6 ACK/NACK detection

This process extracts the contents of the SNc and SNc status fields and hands this information over to the Downlink controller.

2.6.7   Downlink cell flow

From each ATM cell that arrives from the switch at the LLC layer, the VCI/VPI is read and the corresponding link ID, stored in the link resource table, is determined. The cell is

encapsulated into a LLC DATA PDU and a sequence number is added to uniquely identify this cell on the wireless link. Then, a copy of the PDU is stored in the downlink buffer reserved for the current connection. A timer is set to indicate the expiry time of the PDU. Just before forwarding the cell to the MAC layer in order to be scheduled, an SNc and SNc status is added to the PDU (if there is one available in the SNc table) in order to acknowledge the PDUs for the uplink connection. Furthermore, a timestamp, indicating the moment of arrival of the cell in the FRPC station, and the link ID, indicating to what connection the PDU belongs, is transferred to the MAC layer. If the LLC PDU is a retransmission the priority will set to 'ON' otherwise the priority will be set to 'OFF'.

When the LLC PDU arrives at the MAC layer it is encapsulated in a MAC PDU and is stored in the correct MAC buffer, according to the link ID. The MAC PDU is inserted at the tail of the buffer if the priority is 'OFF'. If the priority is 'ON' the MAC PDU is inserted at the first position, from the head on, where the priority is of the PDU, stored at that position is 'OFF'. Hence a retransmission is inserted behind any retransmissions that already were in the MAC buffer. The 'timestamp' parameter is used by the MAC scheduler to calculate the $t_{max,\ down}$. The link ID is uses to determine the RVCI by looking it up in the Static Lookup Table. At a certain moment the MAC PDU is forwarded to the physical layer (depending on how it was scheduled). The physical layer encapsulates it in a PHY PDU transports the PDU between FRPC and FRP. The physical layer of the FRP transmits the PDU over the air interface.

The physical layer at the PRP knows when to receive a PHY PDU in a certain slot on the basis of the slot assignment information of $(n-2)^{th}$ broadcast cell. The MAC PDU is extracted from the PHY PDU and is forwarded to the MAC layer. At the MAC layer it is decided if a cell is received correctly or incorrectly on basis of an error distribution function which has an average of CLR. The LLC PDU is extracted from the MAC PDU and the LLC PDU and the Receive status are forwarded to the LLC layer. At the LLC layer the PDU, depending on the receives status and the status of the related LLC parameters, table and buffers, is either discarded, forwarded to the UTE, or stored at the PRP Downlink buffer.

2.6.8   Uplink cell flow

From each ATM cell that arrives from the UTE at the LLC layer, the VCI/VPI is read and the corresponding link ID, stored in the link resource table, is determined. The cell is encapsulated into a LLC DATA PDU and a sequence number is added to uniquely identify this cell on the wireless link. Then, a copy of the PDU is stored in the uplink buffer reserved for the current connection. A timer is set to indicate the expiry time of the PDU. Just before forwarding the cell to the MAC layer in order to be scheduled, an SNc and SNc status is added to the PDU (if there is one available in the SNc table) in order to acknowledge the PDUs for the downlink connection. Furthermore the link ID, indicating to what connection the PDU belongs, is transferred to the MAC layer. If the LLC PDU is a retransmission, the priority will set to 'ON' otherwise the priority will be set to 'OFF'.

When the LLC PDU arrives at the MAC layer it is encapsulated in a MAC PDU and is stored in the correct MAC buffer, according to the link ID. The MAC PDU is inserted at the tail of the buffer if the priority is 'OFF'. If the priority is 'ON' the MAC PDU is inserted at the first position, from the head on, where the priority is of the PDU, stored at that position is 'OFF'. Hence a retransmission is inserted behind any retransmissions that already were in the MAC buffer. The link ID is used to determine the RVCI by looking it up in the Static Lookup Table. Just before forwarding the MAC PDU to the physical layer the MAC field is set to the

number of PDUs still waiting in the MAC buffer for that RVCI. The physical layer transmits the PDU over the air interface to the FRP.

The FRP physical layer transports the PDU between to the FRPC physical layer. The MAC PDU is extracted from the PHY PDU and is forwarded to the MAC layer. At the MAC layer it is decided if a cell is received correctly or incorrectly on basis of an error distribution function which has an average of CLR. The LLC PDU is extracted from the MAC PDU and the LLC PDU and the Receive status are forwarded to the LLC layer. At the LLC layer the PDU, depending on the receives status and the status of the related LLC parameters, table and buffers, is either discarded, forwarded to the UTE, or stored at the PRP Downlink buffer.

2.6.9   Priority mechanism

The priority mechanism consists of two parts:

❑   Retransmissions are given priority over normal transmissions

❑   Negative acknowledgements are given priority over positive acknowledgements

When looking at the retransmissions, because of the ToE principle the downlink has an advantage over the uplink. In the downlink, retransmissions are prioritised both over normal transmissions of the same connection and over any cells to be scheduled from other connections. By setting the 'priority' field when sending a cell to the MAC layer, the MAC layer will insert the cell at the head-side of MAC buffer, just after any other cell with the priority field set (this is to maintain the order of retransmissions). Hence cells with priority will be transmitted sooner than cells without priority. Also, because the timestamp of cells that are to be retransmitted is older than that of new cells (of the same connection, but also of other connections) the t_{max} parameter will be lower and the scheduler will assign more bandwidth. However, this off course depends on the CTD as it was established during the connection set-up and the derived Δ_{max} parameter. For the uplink only the priority field plays a role because uplink cells are scheduled by the FRPC scheduler and the t_{max} for uplink cells is estimated for all the cells waiting in the PRP MAC buffer without yet having obtained a slot assignment and the FRPC has no way of knowing whether some of those cells are retransmissions.

2.6.10   Transmit buffer timing

In order to comply with the CTD, the transmit buffer, that is the uplink buffer in the FRPC and the downlink buffer in the PRP, need to decide when the cells waiting in the buffer, are to be transmitted to the switch/UTE. For the FRPC Uplink buffer, the expiry time, t_{exp}, for a cell that arrives just after an erroneous cell is defined as:

$$t_{exp,\,up} = t_{arr,\,frpc} + \Delta_{max,\,up} - \Delta_{schedule,\,up}$$

For the PRP downlink buffer the expiry time is defined as:

$$t_{exp,\,down} = t_{arr,\,prp} + \Delta_{max,\,down} - \Delta_{schedule,\,down}$$

In these expressions, t_{arr} is the arrival time of the cell ate the LLC layer of the FRPC respectively the PRP. The Δ_{max} parameter the link CTD minus the fixed processing delays (as determined in section 2.2.5) and $\Delta_{schedule}$ is an estimation of the time it took the ToE to schedule the cell.

3   Modelling of ARQ in OPNET

3.1   Introduction

In this chapter, first a short description of the OPNET modelling package is provided. Next, a model of the ARQ scheme, proposed in the previous chapter, is developed using a seven-step development process. The model is an enhancement to the existing Wireless ATM Modelling suite and is implemented as a process model that runs in the LLC layer queue module in the FRPC. At the end of the chapter the model scope and its limitations are discussed.

3.2   OPNET

The software tool used to model and simulate the proposed ARQ scheme is the OPNET Modeller/Radio package [Opn98]. It consists of several editors, each representing project development stages including specification, simulation, data collection and data analysis.
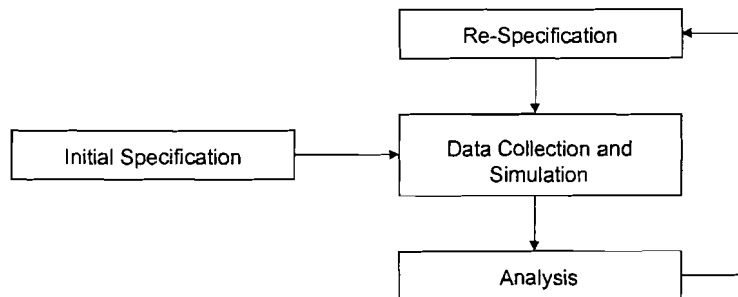
Figure 3.1: OPNET development stages

Figure 3.1 shows these development stages that are performed in a cycle. After the initial specification, simulations are performed and data is collected. After the data is analysed the model may be re-specified. In the following sections a short description of the most important OPNET editors is given including the project editor, network editor, node editor, process editor, parameter and advanced editors. The editors are hierarchically organised with the project editor at the top level. The remaining editors are accessible from within the project editor, but can also be accessed separately.

3.2.1   Project editor

The Project Editor is at the top of the design hierarchy. A project may exist of several networks or variations of the same network. Scenarios are used to perform simulations of different configurations of the network, for instance with different traffic loads. From within the project editor, simulations can be specified (e.g. the data to be collected) and run and the results may be analysed.

3.2.2   Network editor

In the network Editor a network can be created consisting of a number of nodes, connected to each other via links. A network is created in a geographical context, where distances and heights between nodes or sub networks can be specified. The editor supports fixed, mobile and satellite nodes.

3.2.3   Node editor

By clicking on a node in the network editor, the node editor is automatically invoked. A node consists of several modules. A module can have predefined behaviour, such as a transmitter or a receiver or it can have programmable behaviour in case it's a processor or a queue. A queue has the same functionality as a processor but has additional packet queuing facilities. Modules are connected by packet streams, that allow messages to be exchanged by a predefined packet format, or by statistical wires that allow for an exchange of simple information.

3.2.4   Process editor

The behaviour of the programmable modules, processors and queues, is defined in the process editor. It specifies a process model as a state machine with states and transitions between states. The states contain Proto C/C++ statements that represent actions to perform when a process is in a certain state. A module can have several instances of a process model and processes can be created dynamically during a simulation by the same or by another process model running in the module.

3.2.5   Parameter editors

The parameter editors include the link model editor, the power density function (PDF) editor, Antenna pattern editor, modulation curve editor and Interface Control Information (ICI) editor. An ICI (Interface Control Information) is a data structure that is used to establish a formal interface between modules that communicate via some form of interrupt. Typically, ICIs are used to pass indications and requests between protocol layers.

3.2.6   Advanced editors

The probe editor, simulation editor and filter editor are all advanced editors. The probe editor is used to identify sources of statistics and animation that are to be collected during a simulation. With the simulation tool the user can design and run sequences of simulations, each potentially configured with different inputs and/or outputs. The analysis tool is used to plot and process numerical data generated by simulations and the filter editor defines numerical processing that can be applied to data in analysis panels.

3.3   Process Model development methodology

The process model development method used in this chapter consists of seven stages. This section describes the development of the ARQ process model for the FRPC. The ARQ process in the PRP is similar and is therefore not shown here.

3.3.1   Defining the system's context

The first step in the process model development method is to define the system's context of the ARQ process model, specifically in relation to those modules it interacts with. All modules that generate events for the ARQ process are considered to be interdependent and are to be identified as such. Next, the communication mechanisms between the ARQ process and the interdependent modules should be selected and a diagram is developed of the process and interdependent modules as well as the selected communication mechanisms. The ARQ mechanism is based in the LLC and in this way it interacts with the surrounding modules, the Switch and the MAC layer, as shown in Figure 3.2.
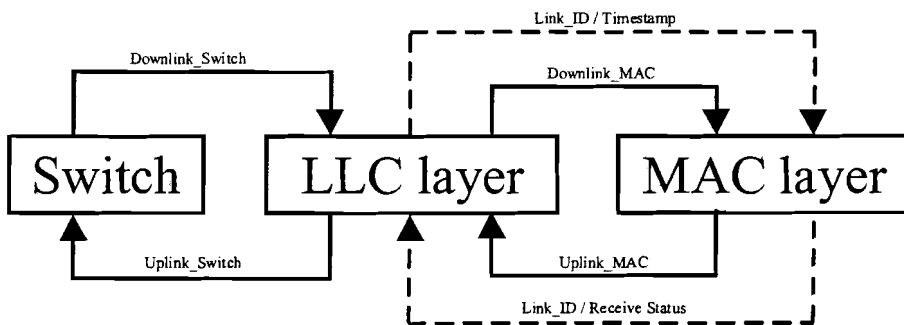

Figure 3.2: Context of LLC layer

The LLC communicates with the switch via packets in the ATM cell format and with the MAC layer via packets in the LLC PDU format, shown in Figure 3.2 as the Downlink_Switch, Uplink_Switch and Downlink_MAC, Uplink_MAC packet streams respectively. The dashed lines indicate the ICIs. ICIs are data structures linked to an interrupt, in this case a stream interrupt, and are used to transfer specific information related to that interrupt. The link_ID is used to identify the connection and the Timestamp is used by the MAC in order to calculate the t_{max} [Pri97].

3.3.2   Process level decomposition

In this stage is determined if a module should be represented by a single process or by multiple processes. In the first case this stage is completed whereas in the latter case it should be determined whether the module is to be represented by multiple processes that are dynamically created, asynchronous co-operating processes or by a hierarchical process organisation to spread complexity over several levels. Also, a root process is to be assigned. To determine the correct approach the activities of the module are analysed and are separated in a simple set of actions.

In this case the LLC has two major functions:

❑   Handling all user traffic from the MAC to the Switch and vice versa

❑   Handover control

Currently the LLC module consists of two processes: FRPC_LLCDis and FRPC_LLCHanCtrl [Meu99]. The FRPC_LLCDis acts as a dispatcher process and is responsible for creating other (child) processes and invoke them if any events occur of interest to those child processes. The FRPC_LLCHanCtrl is such a child process and handles all handover-related actions. It is a natural decision to declare the ARQ process as another child process to spread the complexity. The ARQ process is named FRPC_LLCARQ and handles all downlink and uplink non-wireless-specific packets. The result is shown in Figure 3.3.
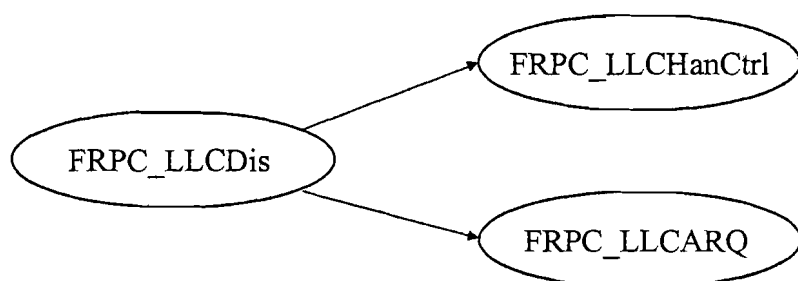

Figure 3.3: Process level composition of the LLC process

3.3.3   Enumeration of events:

In this stage all logical events, i.e. all occurrences that require the activation of a specific process, are identified for the processes as defined in the previous section. The appropriate OPNET event type and corresponding interrupt are selected based on the source of the event. A list of all logical events and the corresponding interrupt is composed for each process.

As determined in the process level decomposition stage the LLC module uses three processes. The FRPC_LLCDis process acts as a dispatcher process whose task is mainly to distribute packets that arrive to the correct child process. The events for the dispatcher process are shown in Table 3.1.

Event name	Event description	Interrupt type
PROCESS_CREATE	Initial event to allow initialisation of the process	Begin simulation
MAC_PDU_ARRIVAL	A MAC_PDU has arrived from the MAC layer and has to be handed over to the appropriate process depending on the type of cell	Stream
ATM_CELL_ARRIVAL	An ATM cell has arrived from the switch and has to be handed over to the FRPC_LLC_ARQ process	Stream

Table 3.1: Events for the dispatcher process

The FRPC_LLCHanCtrl process falls outside the scope of this report and because there is no interaction with the ARQ process it is not further implemented here. The events for the FRPC_LLCARQ process are listed in Table 3.2. Some events are similar to events for the dispatcher process. This is because for those events the FRPC_LLCARQ process is invoked.

Event name	Event description	Interrupt type
PROCESS_CREATE	Initial event to allow initialisation of the process	Invocation by the Dispatcher process
MAC_PDU_ARRIVAL	A MAC_PDU has arrived from the MAC layer	Stream
ATM_CELL_ARRIVAL	An ATM cell has arrived from the switch	Stream
UPLINK_BUFFER_TIMEOUT	One or more cells in the Uplink buffer have expired and need to be transmitted to the Switch	Self
DOWNLINK_BUFFER_TIMEOUT	One or more cells in the Downlink buffer have expired and need to be transmitted to the MAC layer	Self
ACK_PDU_GENERATE	If the number of SNc in the SNc table exceeds a certain limit an ACK_PDU is generated and transmitted to the MAC layer	Self

Table 3.2: Events for the ARQ process

3.3.4   State-level Decomposition of processes

A number of discrete states is determined for each process of the LLC module that form the basis of the State Transition Diagram (STD). The set of selected states should satisfy the following four criteria:

❑   A state corresponds to a particular sequence of events

❑   Events are handled in a specific way as a result of being located in a particular state

❑   Selected states are mutually exclusive and complementary

❑   Each state should represent a blocking point of the process

Because the LLC dispatch process is already implemented it is not described here. Only one state can be defined for the ARQ mechanism: it has only one mode and that is to wait for the arrival of a packet or for the expiration of a timer. Table 3.3 shows the state for the FRPC_LLCARQ.

State name	State description
Idle	Wait for a packet to arrive or for self interrupt

Table 1 States for the ARQ process

3.3.5   Developing the state transition diagram

The purpose of this stage is to combine the set of logical events with the state(s) as deduced in the State-level Decomposition stage in order to construct an event response table that acts as the basis for the STD.

Generally speaking it is only possible for a subset of logical events to occur while the process is in a certain state as the involvement of the process itself is required in the interactions that result in the event. To determine which events can occur while the process is in a given state events are categorised as feasible, infeasible and suppressed. Feasible event are those that are not only possible to receive but that the process may have a use for while occupying a particular state. Infeasible events are events that have no possibility of occurring while the
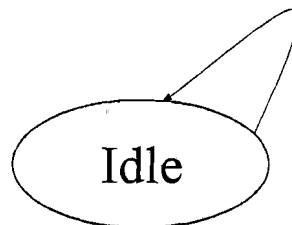

Figure 3.4: ARQ state model

process is in a given state and suppressed events are events that might occur but are of no interest to the process while in a certain state. For efficiency and simplicity invocation of the process for these events should be avoided. In this case there are only feasible events because there is only one state. The Event response table for the idle state is shown in Table 3.4 and shows the actions to be taken when an event occurs under a specific condition. The idle state always returns to itself. Figure 3.4 shows the ARQ state model as deducted so far.

Logical Event	Condition	Action
MAC_PDU_ARRIVAL	receive status = SUCCESS	Detect ACK/NACK, Update exp. RT table, retransmit packets to MAC, Update SNc table, Determine previous lost packets, Store cell in Uplink buffer or forward to switch, forward packets in Uplink buffer if required
	receive status = FAIL	Update Number of lost cells variable
ATM_CELL_ARRIVAL	-	Lookup link_ID, Add SN, Add SNc, Store in Downlink buffer, set expiry time and forward packet to MAC
UPLINK_BUFFER_TIMEOUT	-	Forward packets in Uplink buffer to switch
DOWNLINK_BUFFER_TIMEOUT	-	Forward packets in Downlink buffer to MAC
ACK_PDU_GENERATE	-	Create ACK_PDU, update SNc table, Forward PDU to MAC

Table 2: Event response table for the ARQ process

3.3.6 Specifying Process actions

In this stage first the event-response table is revisited to ensure that all logical actions are specified. In the OPNET proto-C modelling language actions are called executives. A state consists of enter and exit executives. An unforced state blocks between enter and exit executive, waiting for an event to occur. The exit executives of a forced state are executed immediately after completion of the enter executives. Consequently, forced states can not be used to represent true modes of a system but are only used to separate different independent actions as an addition to an unforced state.

In the FRPC_LLCARQ process several independent actions can be distinguished and as a result seven forced states are added to graphically separate these actions that are associated with the events from the event-response table. The forced states are explained below:

3.3.6.1 Downlink Handler

When an ATM cell arrives from the switch, the downlink handler reads the VCI/VPI field and the corresponding link_ID is retrieved. Then it attaches a sequence number, a sequence number 'confirmed' and its corresponding status (ACK/NACK). Then it stores the cell in the downlink buffer, sets the expiry timer and then forwards a copy of the cell to the MAC layer.

3.3.6.2 Downlink retransmission handler

On arrival of a MAC PDU, the downlink retransmission handler extracts the SNc and SNc status and based on the contents of the status field either removes the packet whose SN is equal to this SNc from the downlink buffer or retransmits the packet to the MAC layer. When an LLC ACK PDU arrives, in case of unbalanced traffic it extracts all the SNc and SNc status fields and then either removes the specific packet from the downlink buffer or retransmits it.

3.3.6.3 Uplink handler

Depending on the state of the uplink buffer and the exp_RT table, on arrival of a packet from the MAC, the uplink handler either transmits it immediately to the switch or stores it at the correct position in the uplink buffer. In the last case an expiry timer is set depending on the position in the buffer. Any previous lost packets are detected and the SNc table is updated. Any arriving retransmissions that are expired are discarded.

3.3.6.4 Uplink buffer manager

When the timer for the packet at the top of the buffer expires, the uplink buffer manager will transmit this packet and any other packets in the buffer that are sequential to the one on top. The expRT table is updated, the packets that the packet on the top of the uplink buffer waited for are marked as expired and are considered to be lost definitely.

3.3.6.5 Downlink buffer manager

The downlink buffer manager's task is to limit the size of the downlink buffer by removing packets whose time has expired and need not to be retransmitted again but are just taking up space in the buffer.

3.3.6.6 ACK PDU_generator

If the traffic of a connection is unbalanced, there are not enough packets in the opposite direction to piggyback acknowledgements to. In that case, when necessary, special

ACK PDUs are generated containing those acknowledgements for a number of packets. The number of acknowledgements that can be contained in the AF field depends on the length of sequence numbers.

3.3.7 Selecting an initial state

An initial state is necessary for initialisation purposes of the process and is visited only once at the start of the simulation. The INIT state is responsible for creating and initialising all tables and assigns initial values to state variables and is specially added for this purpose.

Figure 3.5 shows the resulting STD. The dashed lines indicate a conditional transition whereas the straight lines indicate a non-conditional transition. Transitions are executed if the C++/proto C macro statements belonging to the transition become 'true'. The unforced state is shown white and the forced states in black
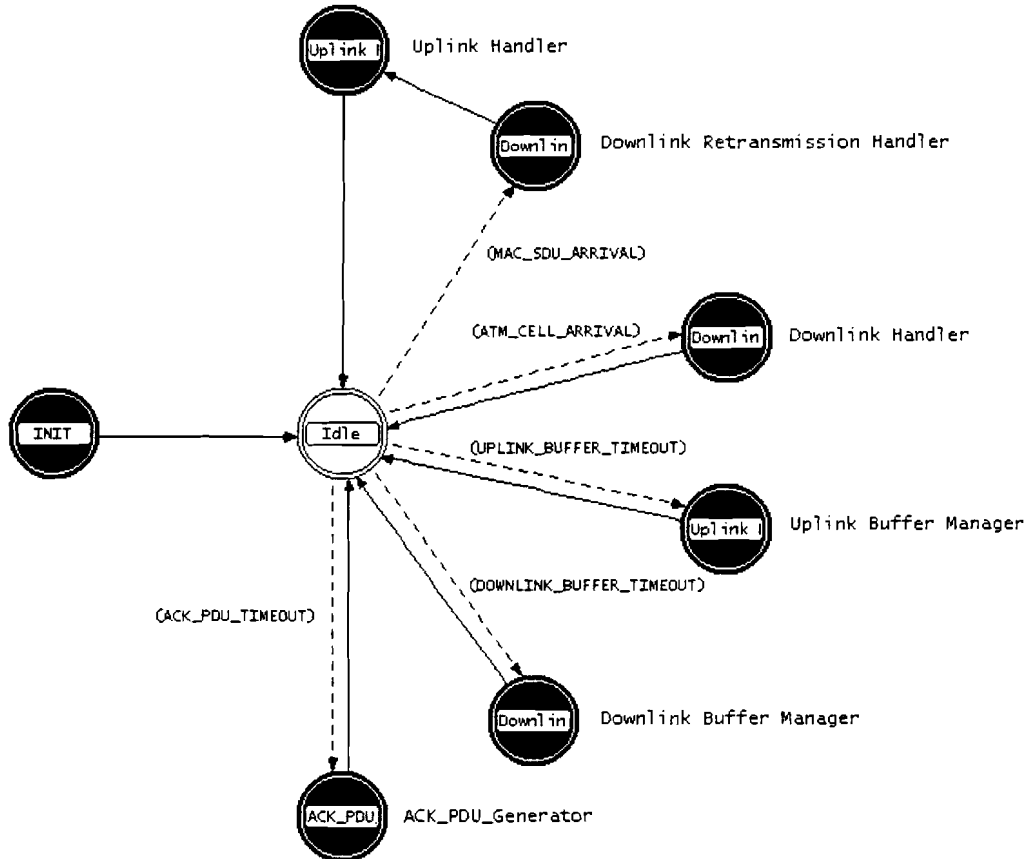

Figure 3.5: State Transition Diagram for the FRPC ARQ process

3.4   Code implementation

Now that the state transition diagram is developed, all actions are specified and an initial state has been selected, the actions to be taken when the process is in a certain state, are implemented by using C++ / proto C language statements. The proto C language consists of a library, referred to as the simulation kernel, with large number of kernel procedures categorised in a number of packages.

3.5   Model scope

The model of the proposed ARQ scheme has some limitations to it. The model is optimised to handle user connections during the connection phase. Errors introduced during the connection set-up are not considered because the current Wireless ATM Modelling Suite does not include the connection set-up. Control information, such as ATM signalling and management cells, that are of concern to the wireless link, are not considered. Also wireless specific cells, e.g. for handover purposes, are not considered. The model assumes an error free return link, that is, Acknowledgements are considered always to be received correctly despite the fact that the cell they were piggybacked to is in error.

4 Simulations

4.1 Introduction

In the previous, an ARQ scheme has been proposed for which an OPNET process model has been developed. The model is implemented as a child process running in the LLC layer module of both the FRPC and PRP. The behaviour of the model is dependent on a number of variables including the frame length, slot duration and a variety of traffic load parameters.
For reference, Table 4.1 lists the parameters, used in the simulation model:

$\Delta_{\text{MAC-SAP}}$	2.16 µs
$\Delta_{\text{LLC-SAP}}$	2.16 µs
$\Delta_{\text{PHY-SAP}}$	2.24 µs
$\Delta_{\text{propagation}}$	100 ns
Slot-time	2.6667 µs
Frame duration	170.667 µs

Table 4.1: Simulation parameters

The main topic if interest is the behaviour of the model for real-time connections for various Cell Loss Ratios in terms of resulting Cell ETE delay and buffer sizes in the FRPC and PRP. A number of simulations have been performed of which the most significant results are presented in the following subsections. First, the influence on the ToE principle is investigated. Then the behaviour of the system for single balanced connections is described. Next, the system's performance for a multiple balanced connections with each having different delay requirements is discussed. Finally the results for a single load scheme with ACK PDU feedback is illustrated.

4.2 ToE interaction

To inform the FRPC of any cells waiting in its buffer, the PRP uses the MAC field of cells going in the uplink direction. The MAC entity in the PRP sets this field to the number of cells waiting in the buffer not yet having obtained a slot assignment.

At the FRPC, the MAC field is used to calculate the number of cells for which a certain t_{max} parameter is valid ($N(c,t)$, see section 2.4). However, when the wireless link is not error-free the MAC field is not available to calculate the $N(c,t)$ parameter. The following simulation results show what occurs due to the absence of the MAC field under certain circumstances.
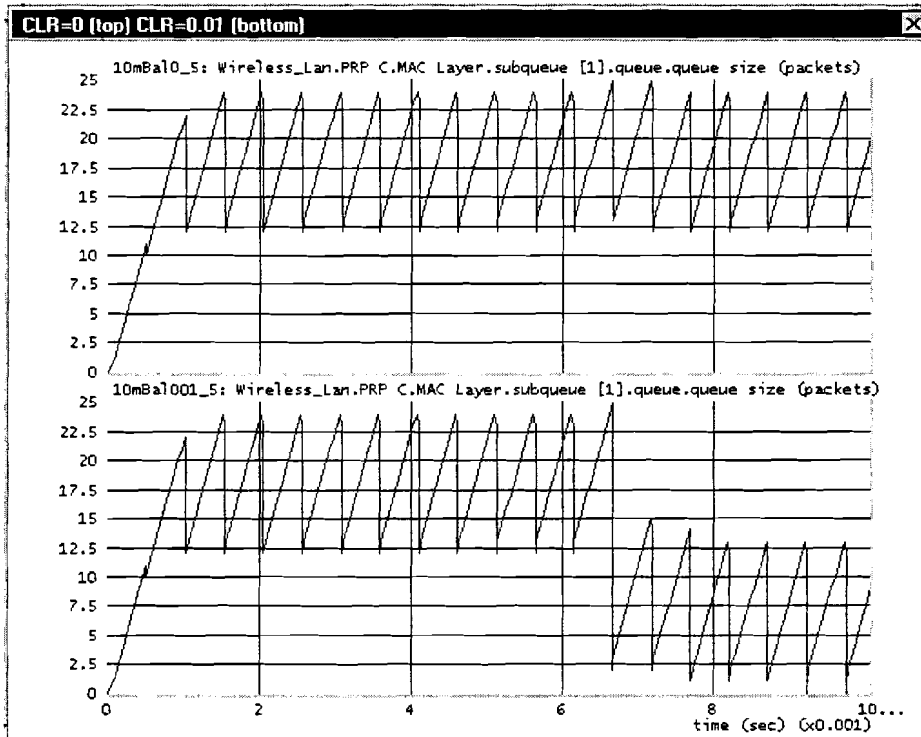
Figure 4.1: Extra slot reservation

4.2.1   Extra slot reservation

Figure 4.1 shows the PRP MAC buffer for a 10Mbit/s balanced connection (i.e. 10Mit/s up and 10Mbit/s down) for a CLR of zero (top) and 0.01 (bottom). Because 10 Mbit/s is a type 1 connection [Meu99], it will be assigned slots in each 3rd frame. This can be seen in Figure 4.1 whereas the period of the sawtooth is exactly the duration of three frames. In the beginning, via a polling slot, the connection obtains bandwidth and then propagates towards a stable slot assignment of 12 slots in each 3rd frame. This equals the average number of 4 cells arriving per frame for a 10Mbit/s-connection. In the bottom part of the figure, however, the scheduler suddenly is assigned 24 slots instead of the normal 12 slots. The explanation for this phenomenon is the following:

If, for the uplink part of a certain connection, in frame n, i cells arrive, $N(c,t)$ is set to the contents of the MAC field of the first cell in the frame minus $M(c,t)$. Then, $M(c,t)$ is set to the contents of the MAC field of the last cell in frame n minus one. Because enough capacity is available the scheduler will reserve $N(c,t)$ slots in the $(n+3)^{th}$ frame. In the upper part of Figure 4.1 this results in:

$$N(c,t) = MAC\ field_1 - M(c,t)\ = 23 - 11 = 12$$
$$M(c,t) = MAC\ field_{12} - 1 = 12 - 1 = 11$$

So each time (as long as 4 cells per frame arrive) 12 slots are reserved. Now let's take a look at the bottom part of the figure. The absence of a MAC field results in the assignment of 24 slots instead of the expected 12 slots. The explanation for this is that, at a certain moment, N(c,t) is calculated as:

$$N(c,t) = MAC\ field_1 - M(c,t) = 23 - 11 = 12$$
$$M(c,t) = MAC\ field_{12} - 1 = 0 - 1 = -1$$

Due to the loss of the last cell, arriving in the $(n+3)^{th}$ frame the MAC field is assumed zero. Then M(c,t) is set to – 1. Then for the succeeding frame N(c,t) is calculated as:

$$N(c,t) = MAC\ field_1 - M(c,t) = 23 - 1 = 24$$
$$M(c,t) = MAC\ field_{12} - 1 = 12 - 1 = 11$$

The results in the reservation of 24 slots in the $(n+6)^{th}$ frame. In this particular case the effects of the assignment are positive because they lead to a lower ETE delay but it could also be the case that bandwidth is wasted, if no cells are waiting in the MAC buffer but slots are still reserved.

4.2.2 Extra frame reservation

Another consequence of a MAC field failure can be seen in Figure 4.2, which shows the same 10 Mbit/s connection as Figure 4.1. In this case the uplink part has obtained an extra frame in which it can transmit cells. Normally a 10 bit/s connection can only transmit cells each 3rd frame because if the PRP demands bandwidth in frame n, the slot reservation is reported in the broadcast cell of frame $(n+1)$ and the cells can be transmitted in frame $(n+3)$ due to the two frame delay of the TDD structure. The extra frame reservation is caused by the (unintentional) invocation of a polling slot. Suppose that in frame n, after receiving the last
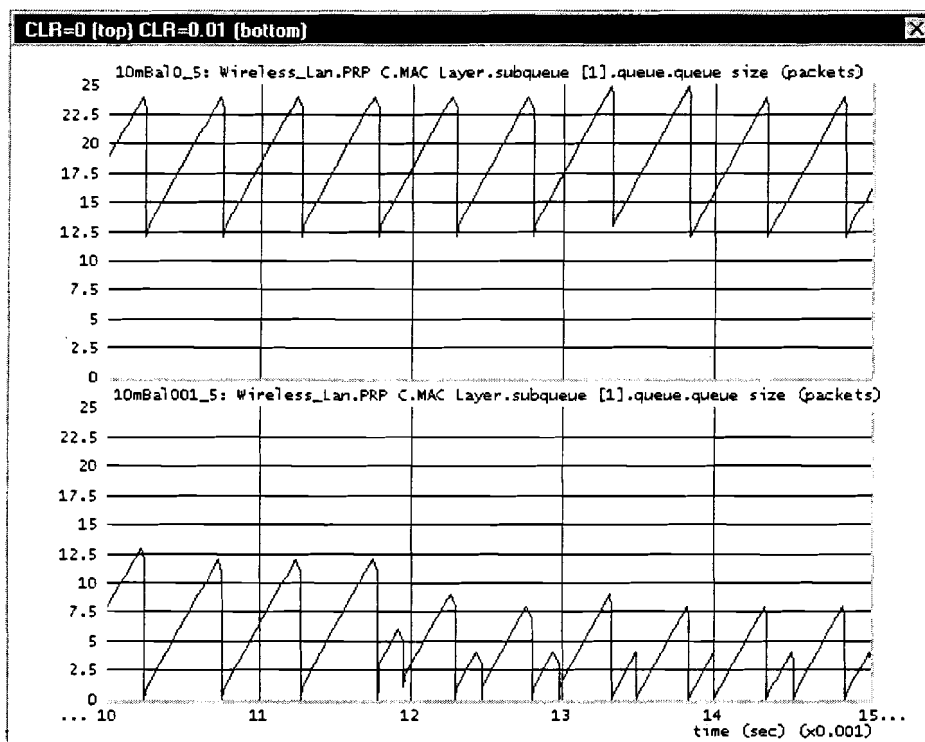

Figure 4.2: Extra frame reservation

cell for that connection the MAC field report that only 1 cell is left in the MAC buffer, then M(c,t) is set to:

$$M(c,t) = MAC\,field - 1 = 1 - 1 = 0$$

Now suppose that in frame (n+1) the first cell in the frame is received in error, then the MAC field equals 0. Now if both N(c,t) and M(c,t) are 0 then a polling slot is inserted at time:

$$t_{polling} = t_{current} + \Delta_{polling}$$

In this case, by coincidence, a polling slot has been inserted, in a frame that the PRP originally was not assigned slots to for this connection, but because there were cells waiting in the MAC buffer, it had the opportunity to report those cells to the FRPC for which slots were assigned in the 3rd frame after the current one. Once the connection has transmitted cells in frame m and there is a constant arrival of cells (which is the case for a CBR connection) it will be assigned slots in all frames $(m+i)$ with i being a multiple of 3. As a result the connection obtains slot assignments in 2 out of 3 frames.

4.3   Balanced traffic

In order to evaluate the performance of the model for CBR traffic with balanced uplink and downlink connections a number of simulations have been performed. First a 10 Mbit/s connection will be investigated for several CLRs. Then a comparison will be made between a 10, 25 and 50 Mbit/s connection for a CLR of 10^{-2}.
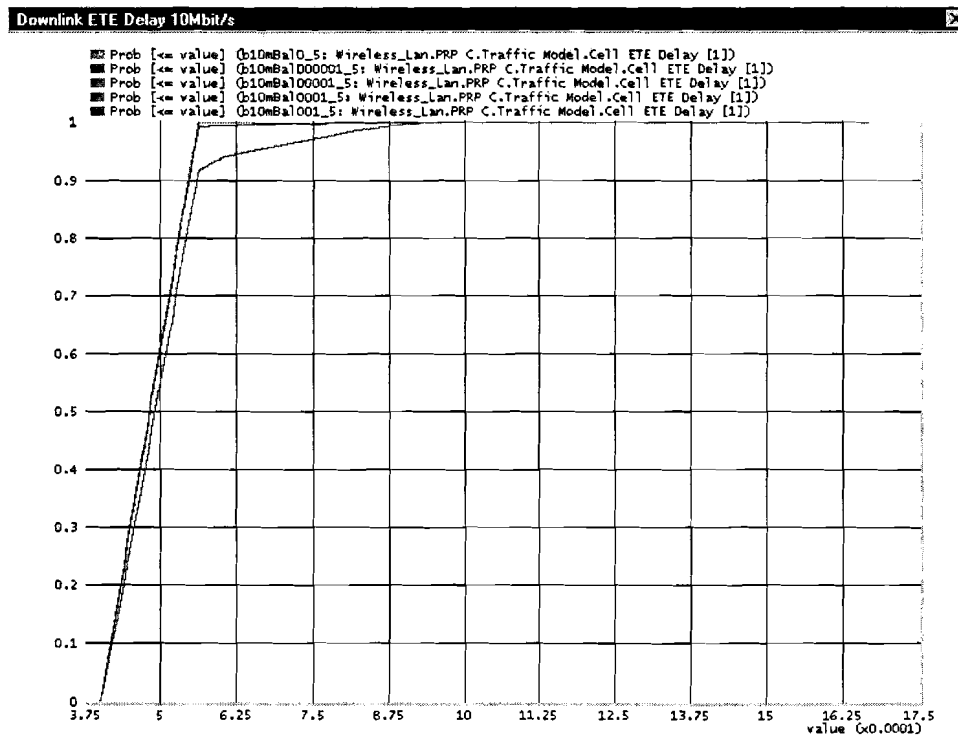

Figure 4.3: CDF downlink ETE delay (10 Mbit/s)

4.3.1   10 Mbit/s connection

To investigate the performance of the model for balanced traffic under several cell loss ratios a 10 Mbit/s connection has been monitored under cell loss ratios of 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2}, and for reference, the error-free case is also included. Figure 4.3 shows the Cumulative Distribution Function (CDF) of the ETE delay for the downlink case.

The figure shows that the ETE delay up to a CLR of 10^{-3} is almost identical. About 99 % of the cells has a delay of less than 0.57 ms. A very small percentage has a higher delay. These are typically retransmissions. The ETE delay distribution for a CLR of 10-2 has a more flat appearance between 0.57 and 0.85 ms due to the increased number of cells that have more than one retransmission. Those cells as well as the cells that are waiting in the PRP downlink buffer fall into this category.
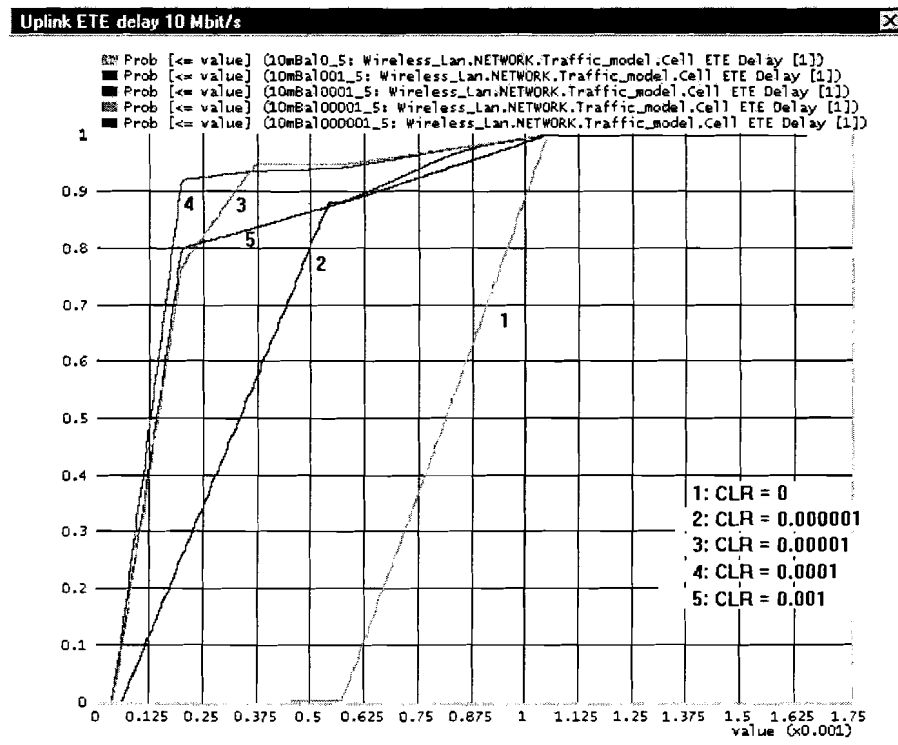

Figure 4.4: CDF uplink ETE delay (10 Mbit/s)

For the uplink case, the ETE delay is influenced by the CLR of the link as well as by the extra frame reservation and scheduling of polling slots due to MAC field failures. This is the reason why the overall delay of the non error-free cases is lower than the error-free case, where cells have a delay between 3 and 6 frames (510 μs to 1020 μs). The extra frame reservation and scheduling of polling slots due to MAC field failures enables the uplink part of the connection to transmit cells more often. For a CLR of 10^{-3} and 10^{-2} about 92 % respectively 80 % of the cells have a delay below 200 μs. The cells having a larger delay are typically retransmissions and cells waiting in the FRPC uplink buffer for retransmissions. For lower cell loss ratios the effect of the extra frame reservation and scheduling of polling slots is less because there are less MAC field errors. This explains the larger delay spread for the CLR of 10^{-4} and 10^{-5}. For the CLR=10^{-5} case as no polling slots were activated in a frame previously unoccupied and as a result, the three frame cycle was maintained resulting in a larger delay spread compared to

the other non error-free cases. For all cases for the vast majority of cells the ETE delay is below 1.1 ms.

4.3.2   Comparison 10/25/50 Mbit/s

Next to the 10 Mbit/s connection, simulations were performed for a 25 Mbit/s and for a 50 Mbit/s connection, equal to a traffic load of 1/3 and 2/3 respectively. To show the performance under a relatively high cell loss ratio the CLR for this simulation was set to 10^{-2}. The outcome is presented in the form of a comparison between the different bit rates.

Figure 4.5 shows the ETE delay for the downlink part, with from left to right 10, 25 and 50 Mbit/s respectively. For all connections the majority of the cells have a delay below three frames and more than 99 % is below 1 ms. The peak values are 1.6 ms, 1.5 ms and 1.25 ms for the 10, 25, 50 Mbit/s connections respectively. The figure illustrates that a higher bit rate results in a higher minimum delay, a higher delay spread and a lower maximum delay. The uplink part of the connections, shown in figure 4.6, shows the same behaviour. Most cells have a delay below 1 ms and the peak value is approximately 1.6 ms.
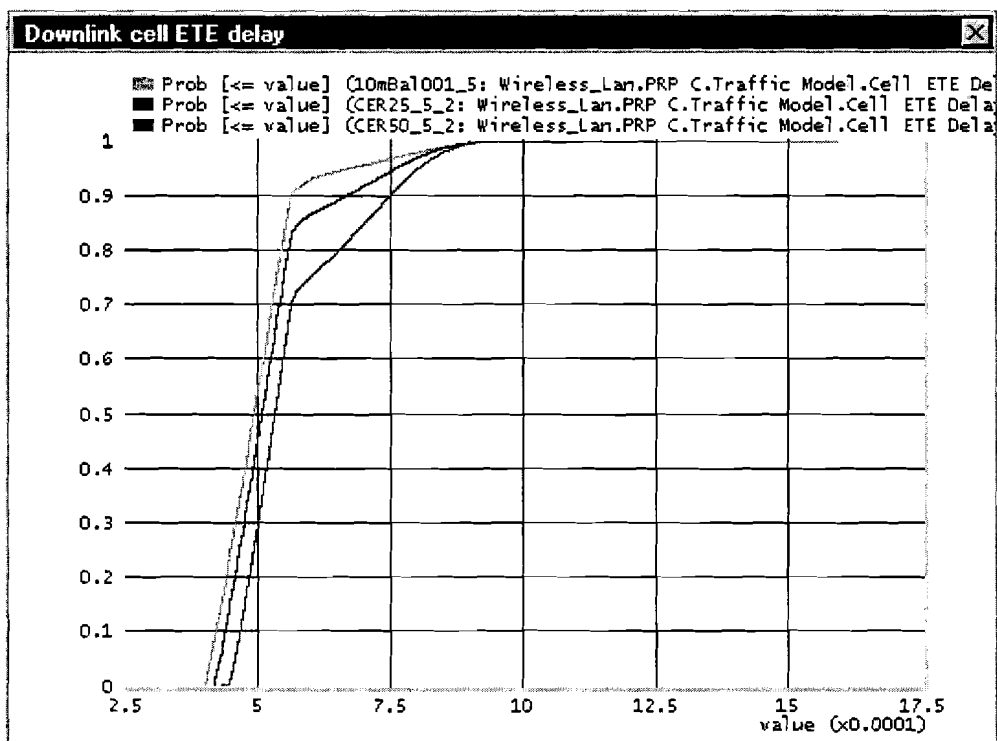

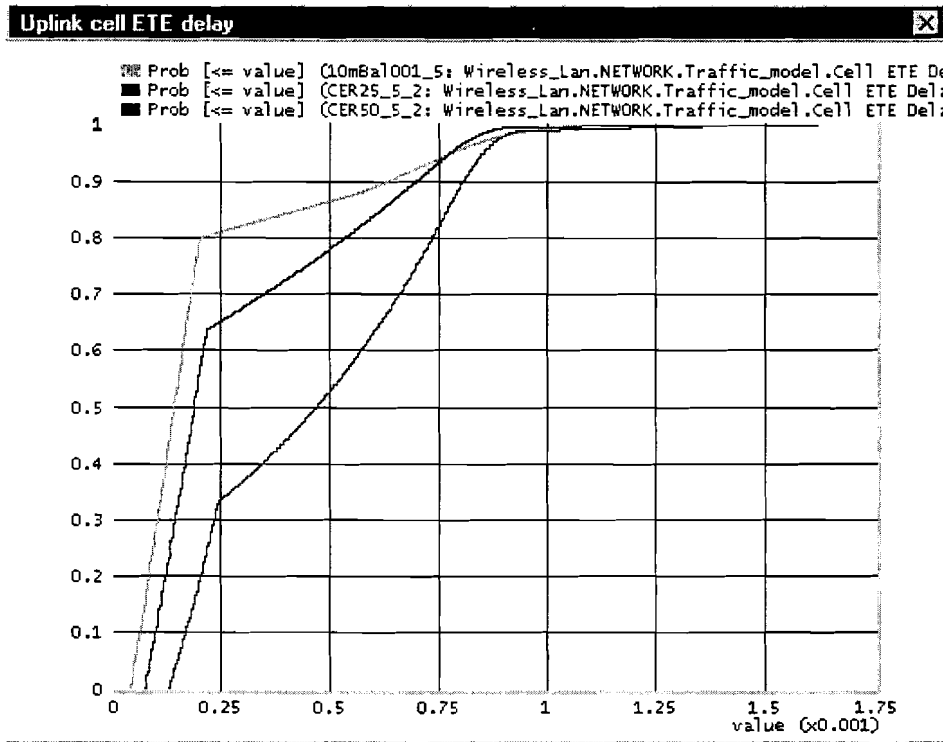*Figure 4.5: CDF downlink ETE delay 10/25/50 Mbit/s*

Figure 4.6: CDF uplink ETE delay 10/25/50 Mbit/s

4.4   Multiple connections

For single balanced traffic the Δ_{max} parameter does not play an important role. However, if there are more connections, the scheduler will use the Δ_{max} parameter to prioritise cells that have the lowest resulting t_{max}. For this, a simulation has been carried out with five balanced 10 Mbit/s connections, each with different delay requirements. The Δ_{max} for the connections is set to 4, 6, 8, 10 and 12 ms respectively and the CLR is 10^{-3}.

Figure 4.7 shows the resulting downlink ETE delay. This time the results are presented in a different way, namely as a histogram with the sample distribution. The picture shows that for all connections, the largest concentration of cells has a delay between 0.4 and 0.6 ms. For the connections with a higher Δ_{max}, the maximum delay is higher, up to 3 ms for the connection with a Δ_{max} of 12 ms but for all connections the ETE delay was well below their allowed maximum.

For the uplink case in Figure 4.8, the largest concentration of cells has an ETE delay between 0.1 and 0.7 ms. The connection with a Δ_{max} of 4 ms has a maximum delay of 1.7 ms, which is larger when compared to the case of a single 10 Mbit/s connection. For the connections with a higher Δ_{max}, the maximum delay is higher, up to 4.5 ms for the connection with a Δ_{max} of 12 ms but for all connections, as in the downlink case, the ETE delay was well below the allowed maximum (link CTD).
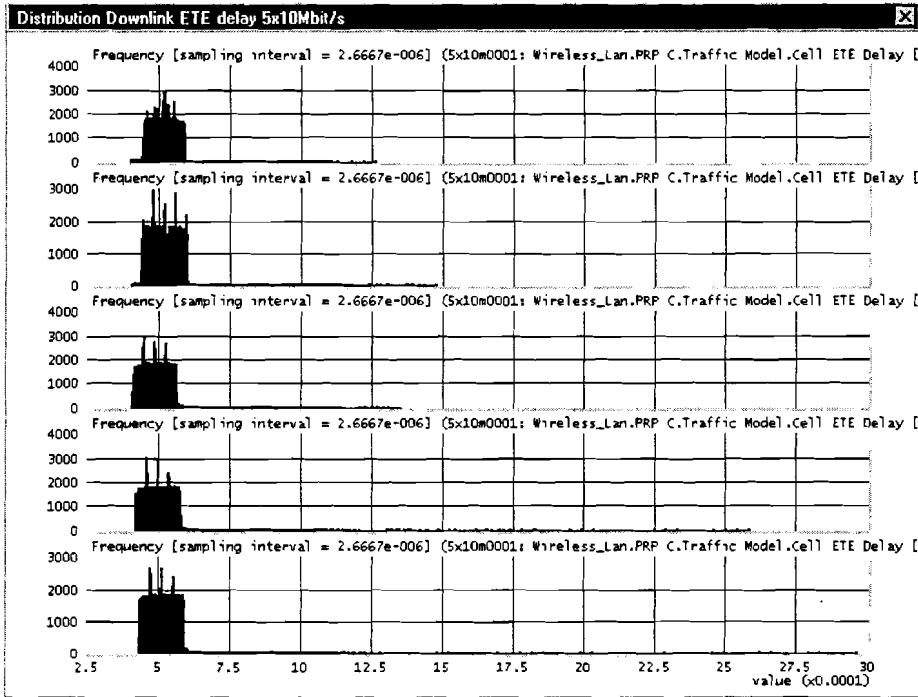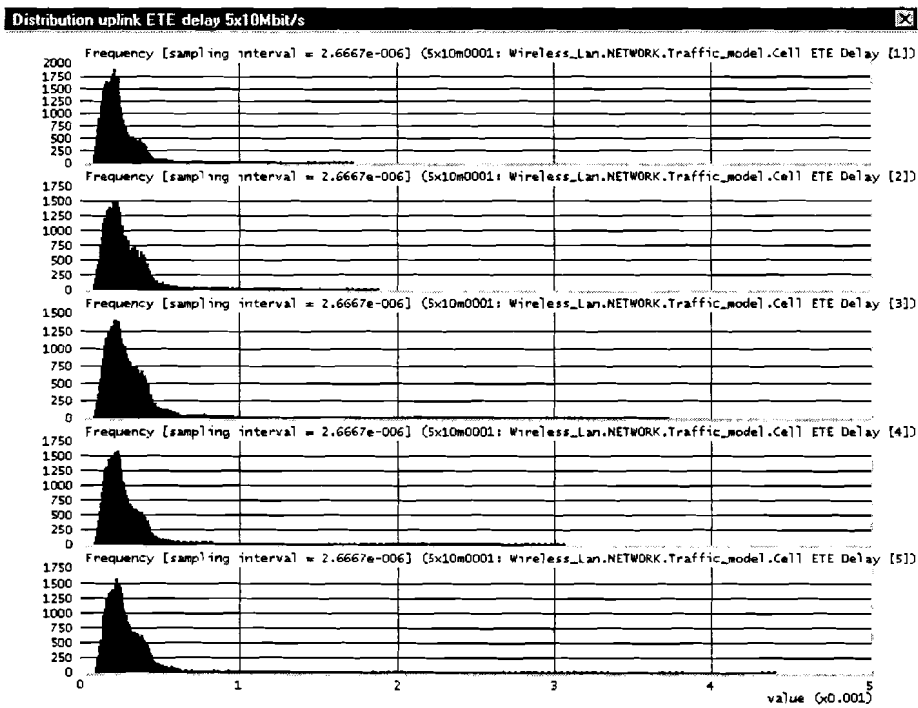
Figure 4.7: Downlink ETE delay 5x10 Mbit/s

Figure 4.8: Uplink ETE delay 5x10 Mbit/s

4.5   Buffer sizes

In the simulations the sizes of the buffers, utilised in the system, has been set to unlimited. In real-life systems the size of the buffers is limited to the amount of memory present in the system. In the model a separation has been made between the MAC buffers and the LLC buffers to demonstrate the behaviour of the buffers as a result of a non error-free link and the use of an ARQ scheme. As a result, cells are moved from the LLC buffers to the MAC buffers. In a real-life system these buffers are combined.

Figure 4.9 shows the typical behaviour of the LLC buffers. The upper part shows the FRPC downlink buffer and the lower part shows the FRPC uplink buffer for a 25 Mbit/s connection with a CLR of 10^{-2}. The two buffers have a quite different behaviour. The behaviour of the transmit buffer (the downlink buffer in the FRPC and the uplink buffer in the PRP) is due to the following:

There is a constant arrival of cells coming from the fixed network, which, in this case averages 10 cells per frame and which are stored in the transmit buffer. Cells are removed when the are acknowledged positively. However, since the uplink traffic and downlink traffic is generated by independent sources there is a variation in the inter-arrival times of cells. Also, at the start-up, it takes a while before the PRP is allowed to transmit, during which there is only an arrival of cells but no cells are removed from the transmit buffer. Finally, the removal of cells from the transmit buffer depends on the number of slots the opposite direction is assigned in a frame, which may vary over time. The three factors explain the variation over time of the number of cells in the transmit buffer.
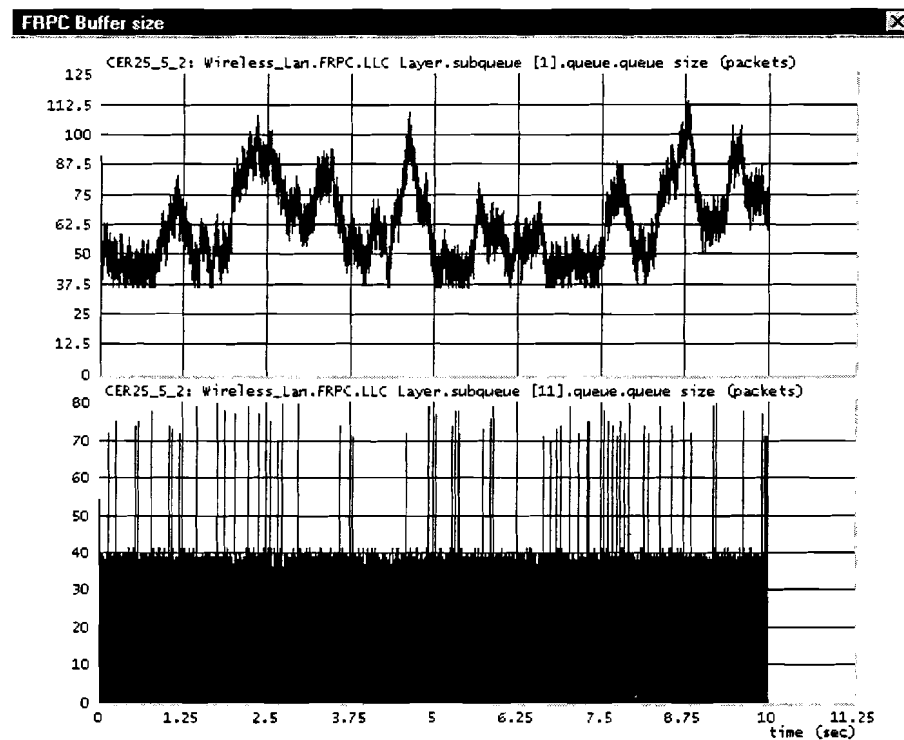

Figure 4.9: FRPC LLC buffers

As for the receive buffer (the uplink buffer in the FRPC and the downlink buffer in the PRP), the behaviour depends directly on the number of cells that get lost because cells are only stored in this buffer if a previous cell has been lost and is not yet retransmitted again. For low cell loss ratios the buffer will empty most of the time. A 'peak' will occur in case a cell was lost. The succeeding cells are stored until that cell is retransmitted. Then the buffer will be empty again. For higher cell loss ratios, as is the case here, there are high and low peaks because a cell may be retransmitted more than once. Also, the average time between cell failures is shorter, so most of the time the buffer will not be empty.

Next to the used memory resources, buffer sizes are also important as an indication for the length of the sequence numbers. To identify each cell, it has a unique sequence number. To limit the overhead on the wireless link, sequence numbers in real-life systems are chosen from a limited set. For example, if the maximum sequence number is 100, then 77 represents a 'newer' cell than 76 but 100 is a 'newer' cell than 1 in which case cell 1 is assumed not to be a retransmission. The length should be set to a large enough value to make sure that the 'old' cell with sequence number 1 is not present in the system anymore.

The identification of cells is most important whenever a cell is being looked up in a LLC layer buffer. As a result, the maximum number of cells waiting in a buffer is an indication of the minimum length for the sequence numbers. The number of cells in the buffer depends on the bit rate of the connection and on the CLR of the wireless link. Table 4.2 shows the maximum number of cells present at any time in all buffers for all simulations performed with a CLR of 10^{-2}.

	10 Mbit/s	25 Mbit/s	50 Mbit/s	5 x 10 Mbit/s
FRPC downlink buffer	142	114	351	57
FRPC uplink buffer	45	80	163	31
PRP downlink buffer	22	54	81	106
PRP uplink buffer	81	302	280	130

Table4.2: Maximum number of cells in LLC buffers

To estimate the SN length, a relatively high CLR is chosen to make sure the system can cope in case the CLR is higher during a short period. Although the number of cells in the transmit buffer is higher, the number of cells in the receive buffer is taken as the basis for the estimation because the number of cells in the transmit buffer can be limited by using an ACK PDU, which will be cheaper than using a larger SN field. The SN length is now determined by using the FRPC uplink buffer and this leads to a minimum size of eight bits for the SN field in the LLC DATA PDU.

4.6   Unbalanced traffic

When traffic is unbalanced, that is, if the downlink has a different bit rate than the uplink, or the traffic is simplex, ACK PDUs are necessary to request the transmitting end for retransmissions and to provide feedback to the transmitter for updating the transmit buffer. The sooner an ACK PDU is sent back to the transmitter the sooner it can retransmit cells, also the transmit buffer size is limited. However, the overhead increases if more ACK PDUs are sent and if the capacity of the ACK PDU is not utilised to its full extend.

Figure 4.10 shows the downlink ETE delay for simplex downlink traffic. For this simulation a 10 Mbit/s connection was used and the CLR was 10^{-2}. The goal of this simulation was the resulting ETE delay for several sizes of the ACK PDU. From left to right, the figure shows the resulting ETE delay for an ACK PDU size of 25, 50 and 75 respectively. This means that there are 25, 50 or 76 acknowledgements in the AF field. An ACK PDU is sent as soon as there are enough sequence numbers in the SNc table to fill a complete ACK PDU. The actual number of sequence numbers an ACK PDU can contain depends on the length chosen for the sequence numbers and the resulting slot-size.

The figure shows that 99 % of the cells have a delay lower than 2, 3 and 4 ms and the peak values are 3, 5 and 7 ms for the 25, 50 and 75 case respectively. In, general, the longer the algorithm waits before sending an ACK PDU, the longer the ETE delay but the resulting ETE delay is not linear with the arrival time of ACK PDUs at the FRPC because , on average, there will also be more requests for retransmission (sequence numbers with 'NACK') per ACK PDU.

It is clear that the ETE for unbalanced traffic is larger when compared to balanced traffic. This is due to the fact that the resulting roundtrip delay time is larger. For an ACK PDU size of 25, the average inter-arrival time at the FRPC is approximately 1 ms. For ACK PDU sizes of 50 and 75 this is 2ms and 3 ms respectively. This results in an average uplink bit rate of 440 Kbit/s, 220 Kbit/s and 147 Kbit/s respectively which can be considered as overhead.
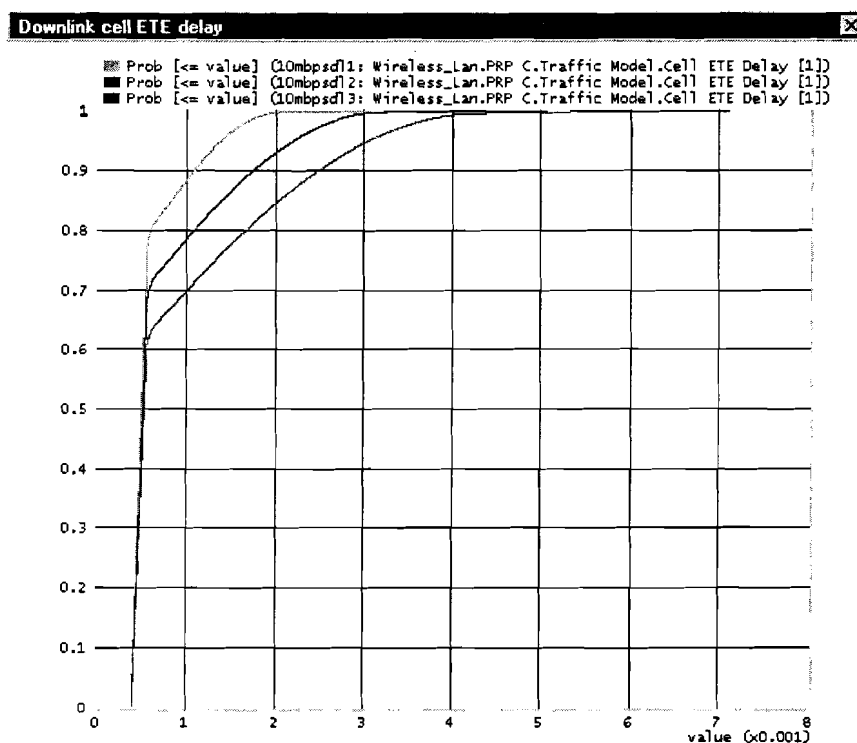

Figure 4.10: CDF downlink ETE delay 10 Mbit/s unbalanced

5   Conclusions and recommendations

5.1   Conclusions

In this chapter a summary of the main results is given and a number of conclusions are drawn. Furthermore, a number of recommendations are presented with respect to further research.

The simulations show that due to a MAC field failure, the scheduler in the FRPC is incorrectly informed about the number of cells waiting in the PRP MAC buffer. In the current implementation each uplink cell informs the scheduler on the number of cells not yet having obtained a slot assignment which actually results in some overhead in the system. In this implementation a MAC field failure in some cases, as illustrated in chapter 4, leads to a scheduling error with, as a result, the reservation of slots in a previously unoccupied frame and extra scheduling of polling slots. From an 'ARQ' point of view this has a positive consequence, as cells can be transmitted more regularly, making the algorithm faster, resulting in a lower ETE delay. However since the extra bandwidth assignment is uncontrolled, and the reservation of extra polling slots also could lead to assignment of slots even if the PRP has nothing to transmit this phenomenon is undesired. It is wiser to assign extra slots in a more controlled way (see section 5.2).

The results of the simulations with regard to the sizes of buffers show that the amount of memory needed for cell storage is not critical. In the worst case, for a 50 Mbit/s connection with a CLR of 10^{-2}, 350 needed to be stored. This equals a memory of less than 20 Kbytes. For multiple connections, even if all connections would have a peak behaviour at the same time the memory would still be limited to approximately 40 Kbytes.

Next to the used memory resources, buffer sizes, especially the receive buffers, are also important as an indication for the length of the sequence numbers. This leads to minimum size for the sequence numbers of eight bits, resulting in an ARQ overhead with regard to the extended cell length of approximately 4 %. The total overhead may be slightly larger if ACK PDUs are used.

Perhaps the most important conclusion of the performed simulation is that performing retransmissions by the use of the suggested ARQ scheme is feasible for real-time ATM services, leading to virtual error-free links. The peak ETE delay in all simulations for all single balanced connections remains below 2 ms whereas the vast majority of cells has an ETE delay below 1ms.

The suggested ARQ scheme should be considered as a first step to extend the existing 60 GHz wireless ATM system with retransmission capability for real-time as well as non real-time services. However the current implementation has two disadvantages to it:

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First, if, for whatever reasons a sequence number gets mutilated or the transmitter sends a cell with an invalid sequence number, The algorithm, in case that specific cell is lost, might detect, identify and report back to the transmitter a false sequence number. This can lead to an unlimited propagation of error because the Exp. RT table at the receiver will not be correct and future cells-in-error might be identified incorrect as well.

Secondly, the transmitter needs to retransmit cells in the order they are acknowledged to the transmitter or the same effect happens as described in the previous paragraph. However this might not be the case if a non error-free return link is considered. In this case a single retransmission scheme is preferred because in this way the problem of identification of retransmitted cells is avoided, since only the distinction between a retransmitted an a non-retransmitted cell needs to be made. Theoretically, a single retransmission scheme will improve to cell loss ratio on the wireless link from CLR to CLR^2. In case the 'raw' cell loss ratio on the wireless link is in the order of 10^{-6} or lower (which is currently the case for the downlink, but not for the uplink) this improvement will be sufficient.

Finally, the following presents a summary of the main conclusions:

❑   Virtual error-free links real-time ATM services is achievable

❑   Sequence number length ≥ 8 bits

❑   Overhead is approximately 4 %

❑   A single retransmission scheme is preferred if the CLR is low

5.2   Recommendations

After having reviewed the outcome of the simulations and having gained experience with the wireless ATM model suite, there are a number of recommendations to be made with respect to the improvement of the system and with respect to topics for further research.

First of all, from the simulations it became clear that if a connection has the ability to transmit cells in each frame, the dell ETE delay will be lower, and an applied ARQ scheme will be faster. In general, the traffic should be more equally spread over the frames. Also, with respect to CBR traffic going in the uplink direction, buffer sizes could be limited if the connection is assigned bandwidth faster at the connection start-up, instead of having to wait for a polling slot. Some sort of traffic shaping, included in a traffic control scheme could achieve this.

Another result from the simulations is the influence of a MAC field failure on the scheduler entity. In general, unwanted scheduling of slots and polling slots should be avoided. A possible approach is, in case a cell is lost, containing the number of cells waiting at the PRP MAC buffer for the specific CBR connection, to set the number of reserved slots for the $(n+2)^{th}$ frame to the average number of arriving cells per frame for that connection. In this approach it is assumed that the connection is able to transmit in each frame.

In the proposed ARQ scheme in this thesis, cells are identified at the wireless link by the combination of link ID and sequence number. The protocol is situated in the LLC layer and as such has no knowledge of the frame structure. It is also possible to identify cells by means of the frame number and slot number. If the transmitter stores the cell together with the frame

number and slot number in which it is transmitted and the receiver reports the frame number and slots numbers in which a erroneous cell was received back to the transmitter can identify the cell by looking it up in the buffer. The broadcast cell can be used to inform the PRPs of the slot assignments for retransmissions. Since the broadcast cell then contains more valuable information it might be wise to implement a stronger FEC code for the broadcast cell only for improved protection. The advantage of this approach is that identification of lost cells is easier and faster. Further research, however, is needed to investigate the possibilities of this approach.

Another topic for further research is the behaviour of the ARQ scheme for VBR traffic and for bit rates below 2.5 Mbit/s. For this last category , it is expected that the ARQ scheme will be relatively slow due to the facts that less then one ATM cell arrives within the duration of a frame, resulting in a slower feedback

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