Error Control for Reliable Multipoint Communication in ATM Networks

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Abstract

Upcoming applications have demanding communication needs. One requirement is the provision of a reliable high performance multipoint communication service. In order to meet high performance requirements and in order to allow an efficient use of network resources, powerful error control mechanisms are required. This paper presents a novel concept for support of multipoint communication in ATM networks. It is based on a new adaptation layer type, called the Reliable Multicast ATM Adaptation Layer (RMC-AAL), and on a new network element, called the Group Communication Server (GCS). A set of error control mechanisms tailored for multipoint communication are integrated into RMC-AAL and GCS. Error control is based on ARQ and FEC schemes, allowing to select the mechanism that is most suitable for the application requirements in a specific communication scenario. The functionality of adaptation layer and group communication server are described, and a basic implementation architecture is presented. Performance results obtained by means of simulation and analysis are given.

1 Introduction

In the evolution of high speed networking, two developments will be of growing importance. One issue is the fast growing deployment of ATM networks, both in local and in wide area networks. The other issue is the increasing importance of group communication scenarios. Upcoming applications, for example in the areas of computer-supported co-operative work (CSCW), distributed applications and virtual shared memory systems require point-to-multipoint (Multicast, 1:N) as well as multipoint-to-multipoint (Multipeer, M:N) communication [[1]. For a growing number of applications such as multimedia collaboration systems, the provision of a multicast service with a specific quality of service (QoS) in terms of throughput, delay and reliability is crucial.

If multipoint communication is not supported by the network or by the end-to-end protocols, multiple point-to-point connections must be used for distribution of identical information to the members of a group. The support of multicasting is beneficial in various ways: It saves bandwidth, reduces processing effort for the end systems, reduces the mean delay for the receivers and simplifies addressing and connection management.

Various issues need to be addressed in order to provide group communication services in ATM networks [[2, [3]. Switches need to incorporate a copy function for support of 1:N virtual channels (VCs). Signaling must be capable of managing multipoint connections, and group management functions need to be provided for administration of members joining and leaving a group. Procedures for routing and call admission control (CAC) need to be adapted for multicast communication. Another key problem that must be solved to provide a reliable multipoint service is the recovery from cell losses due to congestion in the switches.

If a reliable service in ATM networks is based on traditional transport protocols like TCP, severe performance degradations may be observed [[4]. Additional problems occur for the provision of a reliable multipoint service, where transmitters need to deal with many receivers and where cell losses occur more frequently.

This paper focuses on suitable error control mechanisms for correction of cell losses. After presenting alternatives for the provision of a basic multipoint service in ATM networks, the problem of potential cell loss is explained in more detail. Then, an overview on existing error control mechanisms and on protocols that apply these mechanisms is given. The conceptual framework for the provision of a reliable multipoint service is presented, comprising of suitable mechanisms, required components, and basic implementation architectures. Results of a perfomance evaluation by analysis and simulation are given which allow the provision of guidelines for appropriate selection of the mechanisms.

2 Multipoint Communication in ATM Networks

2.1 Multipoint Bearer Service in ATM Networks

Applications may require the following types of multipoint communication: one-to-many, many-to-one and many-to-many. There are a number of ways to support these communication types in ATM networks [[5]. Virtual paths and virtual channels may be of the types point-to-point and point-to-multipoint. Many ATM switch designs are already prepared to copy incoming cells to multiple output ports, providing a basic support for multicast communication in ATM networks.

Support of multipoint connections in signaling protocols is currently under development. In the draft recommendation of the signaling protocol for B-ISDN [[6], support of multipoint connections is not yet included. In the User-Network Interface (UNI) specification version 3.0 of the ATM Forum [7], phase 1 signaling is specified which allows the management of point-to-multipoint connections. Multipoint-to-multipoint connections are not supported by phase 1 signaling, but two techniques are proposed for multipeer communication.

According to the first proposal, each node in a group that wishes to communicate has to establish a point-to-multipoint connection to all of the other nodes of the group. N point-to-multipoint connections are required for a group with N members. This solution does not scale well for large groups. For large, long-lived groups, numerous virtual channels need to be maintained. If one receiver joins or leaves a group, every multicast tree must be modified.

According to the second proposal, each node has to establish a point-to-point connection to a ‘Multicast Server’. A point-to-multipoint connection from the Multicast Server to every member of the group is used to transmit messages to the members of the group. This requires N point-to-point connections and one point-to-multipoint connection, improving the scalability significantly. If this approach is selected, mechanisms must be applied in order to distinguish cells of different senders [8, [3]. One possibility is to distinguish the cells based on an identifier in the payload of the cell. The Message Identifier (MID) of AAL3/4 [[9] may be used for this purpose. In this case, MIDs must be negotiated, and a MID demultiplexing function must be integrated into every receiver. AAL5 [[9] allows a simpler implementation of the adaptation layer, but it does not provide a field for demultiplexing cells. If cells of different frames are mixed, the receiver is only able to detect the collision by checksum violation and to discard the affected frames. In order to avoid these collisions, the multiplexing of different VCs onto a single VC needs to be done in a way that every receiver receives all cells of one frame before receiving cells of another frame. Such a mechanism may operate either in reassembly mode or in cut-through mode. In reassembly mode, forwarding of an incoming AAL5 frame starts after the reception of the last cell of this frame. In cut-through mode, already the first incoming cell of a frame may be forwarded if no other frame of the group is in the process of forwarding.

2.2 Cell Loss in ATM Networks

Two factors must be considered which cause ATM networks to discard cells: transmission bit errors in the cell header field due to noise, and buffer overflow in multiplexing or cross connecting equipment. While fibre optic transmission technology allows to keep the bit error probability very low, the most frequent cause for cell loss is buffer overflow. In ATM networks, statistical multiplexing provides a high degree of resource sharing. Short periods of congestion may occur due to statistical correlations among variable bit rate traffic sources, resulting in buffer overflow. The probability for cell loss may vary over a wide range, depending on the strategy for usage parameter control (UPC) and call admission control which is applied. If very low cell loss probabilities are to be guaranteed even for highly bursty sources, only part of the network resources may be utilised. Utilisation may be increased on the risk of higher cell loss rates. Cell losses due to buffer overflow occur during situations of congestion, caused by superpositon of traffic bursts. Therefore, they do not occur randomly distributed, but in bursts and show a highly correlated characteristic [[10, [11]. If a reliable service has to be provided, mechanisms are required which are able to handle this type of error efficiently. For ATM multicast connections, the problem of cell losses is even more crucial than for unicast connections. Collisions of the multicast VC with different unicast VCs may occur independently at every output port of a switch. For multicast switches with dedicated copy networks, additional collisions may occur for correlated arrivals of bursts in different multicast VCs [[12].

2.3 Error Control Mechanisms

For applications that cannot tolerate the cell losses of the ATM bearer service, error control mechanisms are required. Error control consists of two basic steps: error detection and error recovery. For error recovery, two mechanisms are available: Automatic Repeat ReQuest (ARQ) and Forward Error Correction (FEC). Error control is difficult in networks that offer high bandwidth over long distances. High data rates in combination with a long propagation delay result in high bandwidth-delay products, causeing problems for the following reasons:

- End-to-end control actions require a minimum of one round-trip-delay, and retransmissions require large buffers and may introduce high delays;
- Efficient error control with timer-based loss detection is difficult, because delay variations do not allow very accurate timer setting, causing deterioration of the service quality;
- Processing of error control needs to be performed at very high speeds, if no bottle-neck is to be introduced.

ARQ Methods. For go-back-N ARQ protocols, transmitter and receiver implementations may be very simple, and no buffering is required for the receiver. For selective repeat protocols, transmitter and receiver implementations are more complex, and a large buffer is required by the receiver. Processing overhead of ARQ methods is proportional to the number of data and acknowledgement packets that are processed. For point-to-point communication, ARQ mechanisms are well understood, and a number of protocols for data link layer and transport layer, employing these mechanisms, are known. For multicast communication, there are still many open questions concerning acknowledgement and retransmission strategy, achievable performance and implementation. Large groups require that the transmitter stores and manages a large amount of status information of the receivers. The number of retransmissions is growing for larger group sizes, decreasing the achievable performance. Additionally, the transmitter must be capable of processing a large number of control information. If reliable communication is required to every multicast receiver, a substantial part of the transmitter complexity is growing proportionally to the group size. To overcome this problem, a scheme that provides reliable delivery of messages to K out of N receivers may be applied (K-reliable service).

FEC Methods. FEC methods promise a number of advantages for multicast communication in high-speed networks. The delay for error recovery is independent of the distance, and large bandwidth-delay products do not lead to high buffer requirements. In contrast to ARQ mechanisms, FEC is not affected by the number of receivers. However, FEC has two main disadvantages. It is computationally demanding, and it requires constantly additional bandwidth, limiting the achievable efficiency. Additionally, the problem needs to be addressed that cell losses frequently occur in bursts.

A number of proposals exist on how to use FEC for ATM networks. In [[13], the generation of one (res. three) redundant cells in a block of k cells, based on XOR-operation, is proposed. This coding scheme is capable of correcting one (res. two) cell losses in the block, while sequence numbers in the cells are used for loss detection. In [[11], a scheme is proposed where a sequence of cells is arranged as a two-dimensional array and where XOR-operations are performed to generate one redundant cell per row and one per column. For h columns, a burst error of up to h consecutive cell losses may be corrected. Loss detection is performed using the redundant cells of the rows. No cell sequence numbers are required, permitting application of the scheme also for VP and VC connections independent of the adaptation layer protocol. The use of a special Reed-Solomon Code that is called RSE (Reed-Solomon erasure code) was proposed in [[14, 15]. The coder produces h redundant cells from a block of k information cells, and the decoder is capable of correcting up to h cell losses. Cell sequence numbers are required for loss detection.

Hybrid Error Control. Hybrid error control schemes combine ARQ and FEC. Type I hybrid ARQ schemes use FEC only for error correction and a separate system for error detection. In type II hybrid ARQ schemes, coding is used for error detection and for error correction. A code that is only used for error correction is able to correct more missing information than a code that is also used for error detection. In a type I hybrid scheme, the redundancy may be fully utilised for regeneration of missing cells. Applying this scheme reduces the mean number of required retransmissions, which allows to reduce mean delay and jitter.

2.4 Protocols for Error Recovery

Adaptation Layer Protocols. In the B-ISDN protocol reference model it is planned to integrate error control mechanisms into the Service Specific Convergence Sublayer (SSCS) of the adaptation layer [16, 17]. This is called assured mode service [[9]. Up to now, only two SSCS-Protocols that offer error control mechanisms are specified in the B-ISDN recommendations. The Service Specific Connection Oriented Protocol (SSCOP) is subject of standardisation for a SSCS that offers assured mode service for signaling. The protocol provides end-to-end flow control and retransmission of lost or corrupted data frames by operating in either go-back-N or selective retransmission mode. However, SSCOP does not support assured mode multicast connections. For AAL1, a SSCS with FEC is proposed [[9], based on a Reed-Solomon-Code that uses 4 redundant cells for 124 information cells allowing the regeneration of up to four missing cells.

Transport Protocols. Transport protocols that are suitable for a connectionless network layer, as for example TCP, TP4 and XTP, provide more functionality than the functionality that is required for a SSCS-Protocol. These transport protocols need to handle network packets that are received out of sequence without performing error recovery. A SSCS protocol for a reliable service may be simpler, as it may use sequence number gaps for error detection. The TP++ Transport Protocol [[18] is designed for a heterogeneous internetwork with large bandwidth-delay product and is suitable for ATM networks. TP++ uses a type I hybrid ARQ scheme and is at present the only transport protocol for high speed networks with FEC. It is only capable of unicast communication. Up to now, no hybrid ARQ protocol was presented for multicast communication in ATM networks.

Protocol Implementation. While transmission capacity was growing enormously over the last years, protocol processing and system functions in the transport component turned out to be a performance bottleneck. High performance communication subsystems, based on parallel protocol processing [[19], and hybrid architectures with hardware components for time-critical operations [[20, 21] are required for provision of a service with high throughput and low latency. For highest performance, complete VLSI implementations of transport subsystems are planned [[22]. The performance bottleneck of the transport component that can be observed for point-to-point-communication is even more crucial for reliable multipoint connections. For a growing number of receivers, processing of a growing number of control packets and management of a large amount of status information needs to be performed.

Selection of Protocol Mechanisms and Protocol Configuration. In order to offer a wide range of services to the applications for various network parameters, several concepts of flexible communication subsystems are under development. The parallel transport system PATROCLOS [21] is a parallel implementation of a high performance transport system, offering a wide range of protocol mechanisms that may be selected according to the needs of an application. The Flexible Communication SubSystem (FCSS) [23] is a configurable, function-based transport system. It utilises a de-layered communication architecture that performs the complete transport component functionality for a specific data stream. It provides flexibility and dynamics of QoS selection and control, supporting the application-specific configuration of the protocol machines based on automatic selection of protocol mechanisms out of a protocol resource pool. Additionally, a set of predefined service classes is provided. The selection of appropriate protocol mechanisms in combination with the reservation of resources in network and end systems allows to enhance delay and loss characteristic of the ATM bearer service in order to provide applications with a specific service quality [24].

3 Conceptual Framework for Reliable Multipoint Communication in ATM Networks

A conceptual framework was developed that allows the use of error control mechanisms best suited for a specific multipoint communication scenario at locations that allow highest performance. Figure 1 presents the ATM network scenario with multicast mechanisms in the adaptation layer of ATM end systems and in dedicated servers. For large groups, the servers may be used hierarchically.

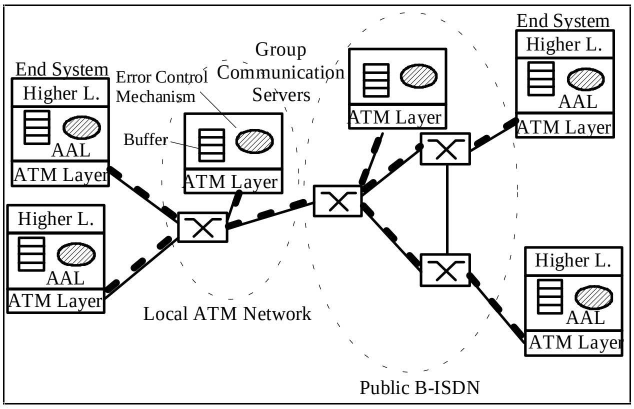

Figure 1:Support for reliable multipoint communication in servers and end systems

3.1 Group Communication Server (GCS)

The presented reliable multicast adaptation layer represents an important step towards a high performance reliable multicast service. Further improvements of performance and efficiency may be achieved by the deployment of dedicated servers in the network that provide support for group communication. In many cases of multicasting, the achievable throughput degrades fast for growing group sizes. A significant advantage can be achieved if a hierarchical approach is chosen for multicast error control. The proposed Group Communication Server (GCS) integrates a range of mechanisms that can be grouped into the following tasks:

- Provision of a high-quality multipoint service with efficient use of network resources;
- Provision of processing support for multicast transmitters;
- Support of heterogeneous hierarchical multicasting;
- Multiplexing support for groups with multiple transmitters.

For the first task, performing error control in the server permits to increase network efficiency and to reduce delays introduced by retransmissions. Allowing retransmissions originating from the server avoids unnecessary retransmissions over common branches of a multicast tree. The integration of FEC mechanisms into the GCS allows regeneration of lost cells and reinsertion of additional redundancy for adjusting the FEC coding scheme according to the needs of subsequent hops.

For the second task, the GCS releases the burden of a transmitter that deals with a large number of receivers, providing scalability. Instead of communicating with all receivers of a group simultaneously, it is possible for a sender to communicate with a small number of GCSs, where each of them provides reliable delivery to a subset of the receivers. Integrating support for reliable high performance multipoint communication into a server allows better use of such dedicated resources.

For the third task, a GCS may use the potential of diversifying outgoing data streams, allowing conversion of different error schemes and support of different qualities of service for individual servers or subgroups. A group communication server may offer the full range of error control mechanisms of the reliable multicast adaptation layer. For end systems, it is not required to implement the full functionality of RMC-AAL. It will be sufficient to have access to a local GCS for participation in a high performance multipoint communication over long distances. The error control mechanisms of individual end systems have only negligible influence onto the overall performance, as simple error control mechanisms are sufficient for communication with a local GCS. If a priority field is used in the frame format, the server is able to distinguish packets of different importance. One example application would be hierarchically coded video. For information with different importance, different FEC codes may be applied inside one VC, or specific frames may be suppressed for certain outgoing links.

For the fourth task, the GCS provides support for multiplexing of AAL5 frames onto a single point-to-multipoint connection. It may be selected by signaling if the GCS operates in reassembly or in cut-through mode.

Figure 2 shows a proposed implementation architecture for a Group Communication Server. Main focus of the design was to achieve a high degree of pipelining. Acknowledgement processing for a large number of receivers is a potential bottleneck. Therefore, dedicated hardware support is provided in the *ARQ manager* unit for filtering and processing of acknowledgements, and for managing the status information of the group and of individual receivers. A component for window processing generates multicast flow control information required by the send manager. Generation of acknowledgements is also performed in the *ARQ manager* unit. The *send manger* unit schedules between ordinary transmissions, retransmissions and acknowledgements. The *connection manager* unit schedules between different connections and is also responsible for rate control and spacing. Additional hardware components are required for CRC, FEC, buffer management, list and timer management. For cell demultiplexing at the receiving side, a content addressable memory (CAM) is used to map the large VPI/VCI address space on smaller internal identifiers. Control of the units is provided by a microprogrammable machine, as it was proposed in [25] for the implementation of a programmable AAL interface.

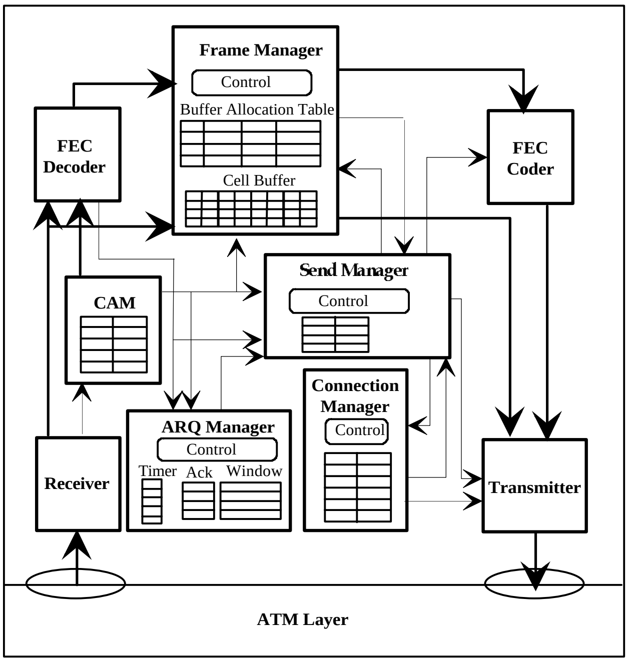

Figure 2: Architecture for the Group Communication Server

3.2 Reliable Multicast ATM Adaptation Layer (RMC-AAL)

The integration of error control mechanisms into the Adaptation Layer needs to be done in a way that high throughput and low latency are guaranteed. In order to offer a reliable and efficient high performance multicast service, the concept of a Reliable Multicast ATM Adaptation Layer (RMC-AAL) was developed. Its ideas are based on the proposal of a configurable extended adaptation layer [24], on the parallel transport system PATROCLOS and on the flexible communication subsystem FCSS.

RMC-AAL extends basic functions of AAL5 by selectable error control mechanisms. Error recovery is based on three schemes: pure ARQ, type I hybrid ARQ and pure FEC. A K-reliable and a fully reliable service are offered. Retransmissions may be sent by multicast or by unicast in selective repeat or go-back-N mode. Complete frames or frame fragments be retransmitted. It can be selected if retransmissions are sent by multicast or individually. When FEC is used, *h* redundant cells for *l•h* information cells are generated based on XOR-operations and matrix interleaving. Frames are distinguished using the 'end-of-message' identifier of AAL5 in the payload type field of the cell header. Frames are identified by a sequence number (with frame sequence numbers of 24 bit) and carry the payload length (16 bit) in the frame header. Cell sequence numbers (6 bit) are provided for detection of missing cells. Two options are available for additional frame based error detection. The payload of a frame may be protected by the cyclic redundancy check CRC-32 of AAL5 for a minimum Hamming distance of four when applied to a payload with up to 11454 bytes. If the mode for retransmission of frame fragments is selected, the payload may be protected by a weighted sum code of 32 bit (WSC-2 of [[18]). This alternative approach requires a more complex processing unit, but allows to evaluate the code for payload protection in any order. For links with a high bit error probability, the per-cell cyclic redundancy check CRC-10 of AAL 3/4 for a minimum Hamming distance of four may be applied. Receivers send acknowledgements periodically, after reception of a frame in which an 'immediate acknowledgement' bit is set, and after detection of a missing frame. Receivers may acknowledge frames or cells cumulative positive by sending a lower window edge, and selective positive or negative by sending bit maps. Similar bit maps are used for selective positive and negative acknowledgments of individual cells. For retransmissions of frame fragments, the first cell of a retransmission frame carries a bit map that identifies retransmitted cells. For flow control, acknowledgements contain the upper window edge of the receiver buffer section reserved for the multipoint connection. Selection of acknowledgement mode, retransmission mode, and time-out periods of RMC-AAL is performed using control frames.

3.3 Signaling

For the management of multipoint connections based on RMC-AAL and GCSs, an extended signaling protocol was developed which is based on the signaling protocols of ITU [[6] and ATM Forum [7]. It allows the negotiation and selection of the set of error control mechanisms used for a specific multipoint connection. Dynamic change of call participation is supported. Information of group membership is stored in a central database, administered by a group management server.

4 Performance Evaluation

It is important to know which error control scheme is best suited for a given situation. Analytical methods were applied and simulations were performed in order to evaluate the achievable performance of the proposed error control schemes for the envisaged multicast scenarios. For modelling the correlation properties of lost cells, a two state Markov model (Gilbert Model) may be applied. Based on the worst case observations of [[11], a probability of 0.3 was used for a cell discard following a cell discard. This is equivalent to cell losses with a mean burst lenght of 1.428 cells. Using this error model, four different error control schemes were simulated in a point-to-multipoint scenario with four receivers. A multicast tree with one common link and four individual links was assumed, and the same error model was applied to all links. A data rate of 100 Mbit/s, a distance of 100 km, and a frame length of 50 cells was used. The first scheme applied selective retransmissions of frames, the second scheme allowed selective retransmission of missing cells. In the third scheme, FEC with 5 redundant cells was combined with selective retransmission of frames, while the same FEC with selective retransmission of missing cells was combined in the fourth scheme. Figure 3 shows the efficiency (relation of usable cells to total number of transmitted cells) of the four schemes for different cell loss probabilities. Figure 4 shows mean delays that were observed. Maximum efficiency may be achieved by the ARQ scheme with retransmissions of individual cells. In this scheme, only discarded cells affect efficiency. If only complete frames are retransmitted, a part of the efficiency is wasted by cells that were already successfully transmitted. For the two FEC schemes, the redundancy of 10% limits the achievable efficiency to 0.9. This disadvantage is traded off by the fact that the delay remains constant over a wide range of cell loss probabilities. Figure 4 also shows a constant delay of 0.4 ms caused by FEC. For the distance and data rate of the simulation, this constant delay is a significant part of the round trip time. Therefore, the mean delay of the ARQ schemes is lower than the mean delay of the hybrid schemes up to a cell loss rate of 10^{-4}. However, for equivalent mean delays the ARQ scheme causes already a large jitter. For longer distances and larger groups, FEC will show an even higher advantage. In order to select an appropriate error control mechanism, the following question is of high interest: up to which limit of cell loss probability results a framebased ARQ scheme in higher efficiency than a framebased hybrid ARQ scheme? An interpolation of the simulation results shows a cell loss probability q_s of approximately $\log(q_s) = -3.4$. Applying analytical methods, a formula was derived for the general efficiency equilibrium: If N denotes the number of receivers, n denotes the number of cells in a packet, and h denotes the number of redundant cells of a FEC scheme, the cell loss probability q_s for which a hybrid ARQ scheme achieves the same efficiency than a simple ARQ scheme was evaluated to:

$$q_s = \frac{h/n}{(n-h)(N+1)} .$$

Applying this result to the parameters of the simulation results in $\log(q_s) = -3.352$, which indicates a high correspondence of analysis and simulation.

Analytical methods were applied in order to evaluate the achievable performance of RMC-AAL in selective repeat (SR) and go-back-N (GBN) mode and to evaluate the potential gain by deployment of GCSs. Figure 5 shows the efficiency of the two retransmission modes in three different scenarios. Scenario 1 represents a basic 1:N multicast without GCS. Scenario 2 represents 1:N multicasting with a GCS that performs retransmissions as multicast. In scenario 3, the GCS uses individual VCs for retransmission. The analysis is based on the following assumptions: protocol processing times may be neglected, acknowledgements are transmitted over a reliable connection, and buffers are sufficiently large. A group of 100 receivers and a data rate of 622 Mbit/s are assumed. Two cases are distinguished. The upper diagram of figure 5 shows the efficiency for an overall distance of 1000 km (distance of 500 km from GCS to the receivers), and the lower diagram shows an overall distance of 505 km (distance of 5 km from GCS to the receivers). The analysis shows that in all cases, the efficiency is increased significantly by the GCS. Highest efficiency may be achieved for scenario 3 and selective repeat. Scenario 2 improves significantly for a shorter distance between GCS and the receivers. Go-back-N retransmissions show acceptable performance only for moderate bandwidth-delay products. Regarding efficiency, scenario 3 and selective repeat should be selected. However, this solution requires the highest implementation complexity for end systems and GCS.

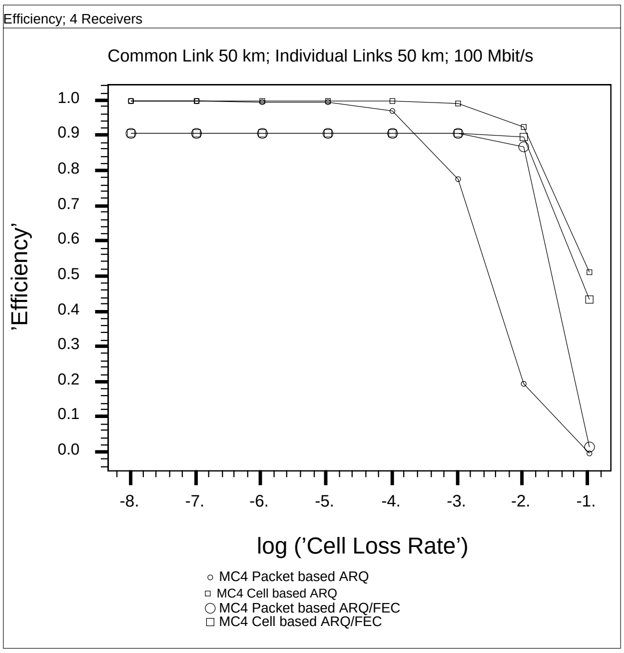

Figure 3: Simulation results for efficiency

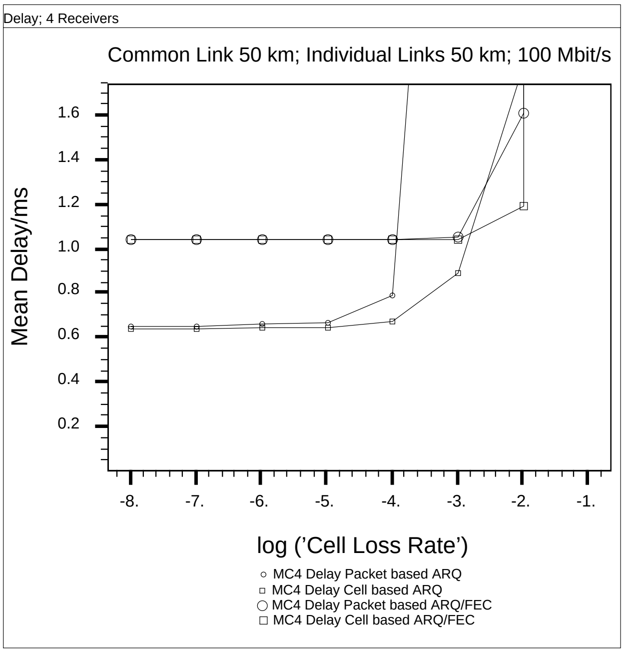

Figure 4: Simulation results for mean delay

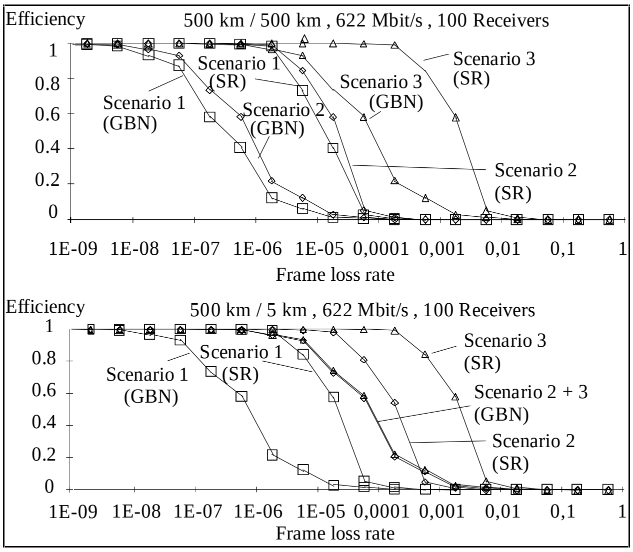

Figure 5: Efficiency analysis for go-back-N and selective repeat in scenarios with and without group communication server

5 Conclusions

It was pointed out that existing strategies do not allow the provision of an efficient and reliable high performance multipoint service in ATM networks. A new concept was presented which has the potential to fulfil the requirements of upcoming distributed applications. It is based on the integration of multicast ARQ and FEC error control schemes into a new adaptation layer type called Reliable Multicast ATM Adaptation Layer (RMC-AAL) and into a new network element called Group Communication Server (GCS). The functionality of these elements is presented, and an implementation architecture is proposed. A first performance evaluation is given which shows the potential benefits of hybrid error control schemes onto service quality of multipoint connections, and potential improvements if GCSs are integrated into the network.

Subject of ongoing work is a more detailed evaluation of the achievable performance, including investigation of the influence of processing times and of limited buffers. Implementation complexity will be evaluated to allow a better comparison of the alternative approaches. This should allow to derive guidelines for the deployment of GCSs and for the selection of the error control scheme best suited for a given situation.

Acknowledgement

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