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# Performance Evaluation of ABR Flow-Control Protocols in a Wireless ATM Network

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**Abstract.** Using an object-oriented simulation model of a basic client–server scenario in a wireless ATM network, we study the impact of handover and error-control protocols on the performance of high-speed data communication by the ABR service class. We present performance results of the ABR flow-control protocols ERICA and ERICA+ and discuss some implications for the protocol design.

**Keywords:** wireless ATM, handover, ABR flow-control, ERICA+

## 1. Introduction

In recent years, dedicated telecommunication networks for voice, data and multi-media communication evolve rapidly towards a worldwide broadband integrated services digital telecommunication network (B-ISDN) based on the Asynchronous Transfer Mode (ATM) as the basic multiplexing, packet-switching and transport technology. The provision of an efficient wired and wireless access to an ATM backbone network is a challenging technical and economic issue (cf. [4,9,12]).

In this paper we consider high-speed data communication in a wireless ATM (WATM) network (see figure 1). For this purpose, we use the ABR service class that is specified in the ATM forum document Traffic Management 4.0 (cf. [1]). The underlying WATM architecture and the used protocol stack of our study are derived from NEC's prototype implementation WATMnet and the ATM forum documents (cf. [2,12,13]). It includes the TDMA/TDD structure and the associated wireless MAC protocol of this system (see figure 2 [12]).

Using an object-oriented simulation model of a basic client–server scenario in a wireless ATM network (see figure 8), we study the impact of the error-prone wireless communication channel and of mobility-management techniques determined by different handover procedures (cf. [2,3,8,17]). In contrast to Veikkolainen's investigation [19], where the impact of handover schemes on a new flow-control algorithm with two control loops spanning the links between a mobile terminal (MT) and its adjacent base station (BS) as well as the latter and a data source are studied, we focus on the performance of the existing ABR flow-control algorithms ERICA and ERICA+ used in the wired ATM network (cf. [5]). Compared to the comprehensive study of different handover strategies performed by Marsan et al. [15], we use simplified models of three different strategies that, from our point of view, cover the basic aspects of the proposed mobility management and call-control techniques very well (cf. [8,11]). Moreover, we investigate the impact of a virtual-source–virtual-destination (VS/VD) concept on the queueing performance and the response of the flow-control protocols.

The paper is organized as follows. Section 2 is devoted to handover management issues of a wireless ATM network. In section 3 we present the ABR flow-control protocols ERICA and ERICA+ used for high-speed data communication. Regarding the impact of handover procedures on an ABR-based data-communication service we present our simulation model and the derived performance results in section 4. Finally, we summarize the findings of our study and discuss some conclusions concerning the protocol design.

## 2. Handover management in a WATM network

Considering the deployment of B-ISDN based on ATM as basic multiplexing, switching and transport technology, there is a growing demand to incorporate wireless subnetworks in a transparent, seamless and economic manner. Using the client–server paradigm, an ATM network provides the basic infrastructure for high-speed data communication among several servers in the wired part of the network and the mobile terminals carrying the mobile clients. The servers offer advanced data services such as web-based information and retrieval services. In our approach, we follow the concept developed by NEC's prototype implementation WATMnet that has influenced the discussion of the ATM forum (cf. [2,12,13]).

The main objective is a seamless integration of mobile terminals and wireless subnetworks into an existing wired ATM network. Hereby no difference between stationary and mobile terminals should be recognized. The QoS requirements of the connections are satisfied by importing new wireless data

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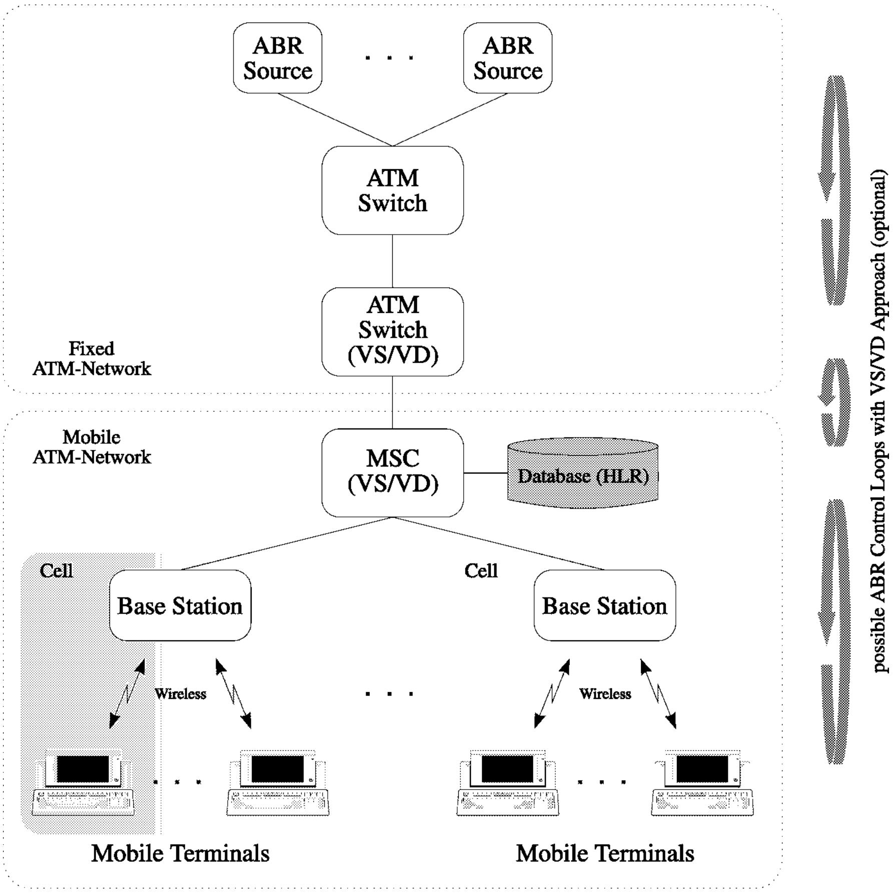


Figure 1. Structure of a generic WATM network scenario.

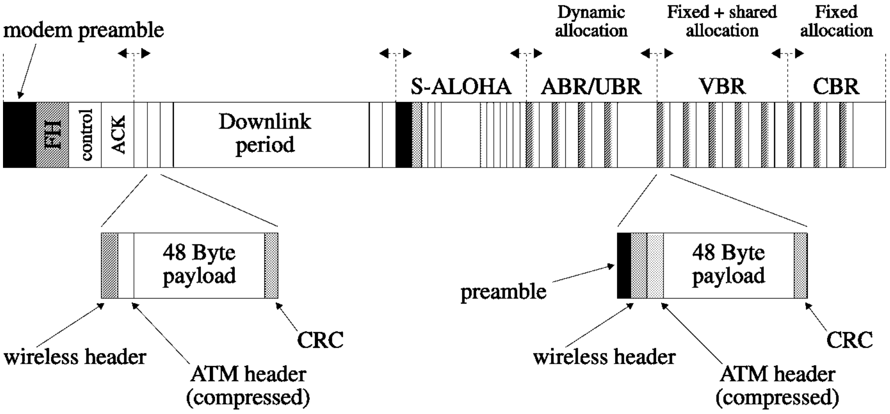


Figure 2. TDMA/TDD frame of WATMnet.

link layer and physical layer functionality below the original ATM adaptation (AAL) and ATM layers, both in the user as well as the control plane. To incorporate WATM into an existing ATM infrastructure, some important issues resulting from deficiencies of wired ATM networks have to be solved. User and network signaling has to be enhanced by appropriate mobility management and call-control functionality to cope with three basic issues arising from the movement of an MT: *location management* (cf. [16]), *connection management and rerouting* (cf. [3,8,11,18]), and *handover management* (cf. [3,8,10,17]).

Handover management includes all activities arising form the transition of a mobile terminal between different radio coverage areas such as the measurement of the actual transmission quality parameters of the radio environment, the initiation and control of the handover process, the selection and seizure of a new radio channel, the search of an appropriate crossover switch (MSC) providing mobility support functions, the establishment of new segments of the virtual channel connections (VCCs) across it, the activation of the new radio port and the data-communication path and finally the update of the data-base record with current location informa-

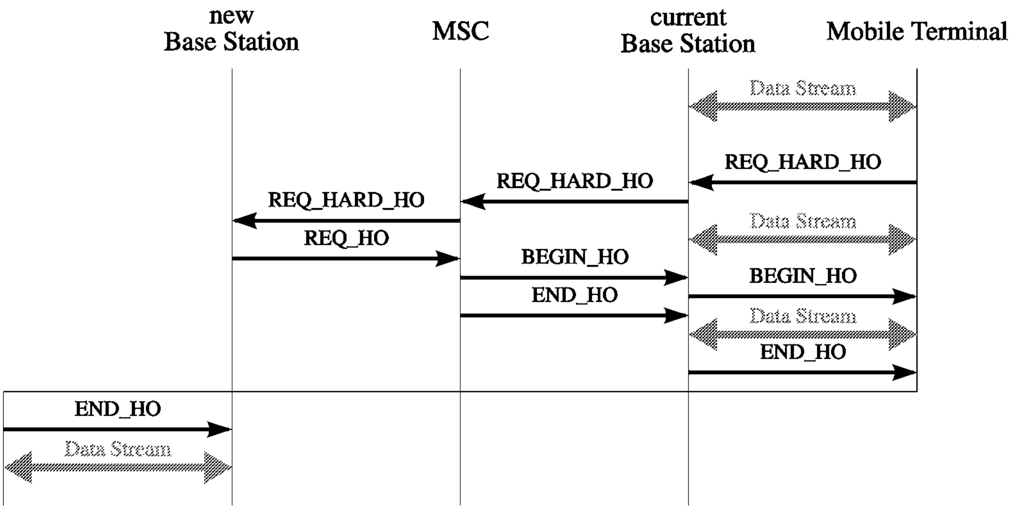


Figure 3. Message sequence chart of hard handover.

tion (cf. [3,8,10,17]). Here interworking with the rerouting and signaling functions is required.

During the communication phase a connection must be permanently maintained since a mobile terminal moves within a certain coverage area and may cross its boundary. In this case the connections must be handed over to a new radio cell whereby a new radio channel is seized and the QoS requirements of the corresponding VCCs must be satisfied in addition to the existing ones within the new radio cell. Regarding data communication the corresponding handover procedures have to guarantee the sequence integrity and loss-free delivery of ATM cells during this transition process. We distinguish a handover within the same area controlled by one base-station controller (BSC) (intra-cell/radio handover) and that one between two distinct base-station controllers (inter-cell/network handover). The latter case involves the rerouting of parts of the VCCs within the wired network and is the complexest process. Therefore, we consider only this case and study its impact on the efficiency of the ABR flow-control protocol (cf. [1,5]).

The corresponding transition between radio channels of different cells can be performed by three different schemes: hard, seamless and soft handover (cf. [4,8,10,11,20]). The features of these handover schemes are as follows:

**Hard handover**. After requesting to establish a communication path (`REQ_HARD_HO`) between the new BS, the associated radio port and the MT, the release of the old channel, as well as the set-up and activation of the new one are performed as concurrent processes. The transition to the new radio channel causes a short disruption of the connection that may result in a loss of data. To guarantee a zero-loss handover, specialized protocols are applied to copy those data packets that were buffered and not sent to the MT so far from the old to the new BS. This scheme works in a mobile-assisted network-controlled environment. It has the advantage that a simple fixed channel-assignment scheme can be used and at any time the MT is attached to only one radio port. The corresponding transfer of signaling messages is depicted in figure 3 where the left-hand side corresponds to the new position of the MT.

**Seamless handover**. The new path and its associated radio channel are established in parallel to the data communication along the existing one. The MT can send uplink a certain time along both. After that period the transition to the new path is performed, the old one is torn down and the data are sent exclusively along the new path (see figure 4). In this scheme the MT uses two uplink channels simultaneously, but it can initiate the handover and seize the channel itself. Combined with dynamic channel assignment there may be some advantage of this strategy.

The proposed backward handover protocol suite including, for example, an MT-initiated connected hard handover scheme resembles most of the ideas of seamless handover (cf. [4,9,15]). It follows a similar concept to establish virtual path and virtual channel connections to an MT along the new BS during a handover transition before the physical handoff to the associated new radio channel is performed. For this reason, we may consider seamless handover as representative of both approaches.

**Soft handover**. In this scheme, apart from the existing data path along the current BS, a new path along the new BS and the associated radio port to the MT is established. Along both ways, data and control messages are transferred in both directions for some time. After a certain period the old path is torn down and the corresponding channel is released (see figure 5). This scheme is very expensive and, hence, not seriously taken into consideration for flow-controlled data communication. It is only considered as a reference model.

For the three schemes we have only shown the cases of an MT-initiated handover where the handover request and all related information is provided by the MT along the old subpath for a hard handover scheme or along the new subpath for a seamless or soft handover scheme (see figures 3–5). The BS initiation is in a way similar. Moreover, we have only sketched a simplified error-free message exchange and

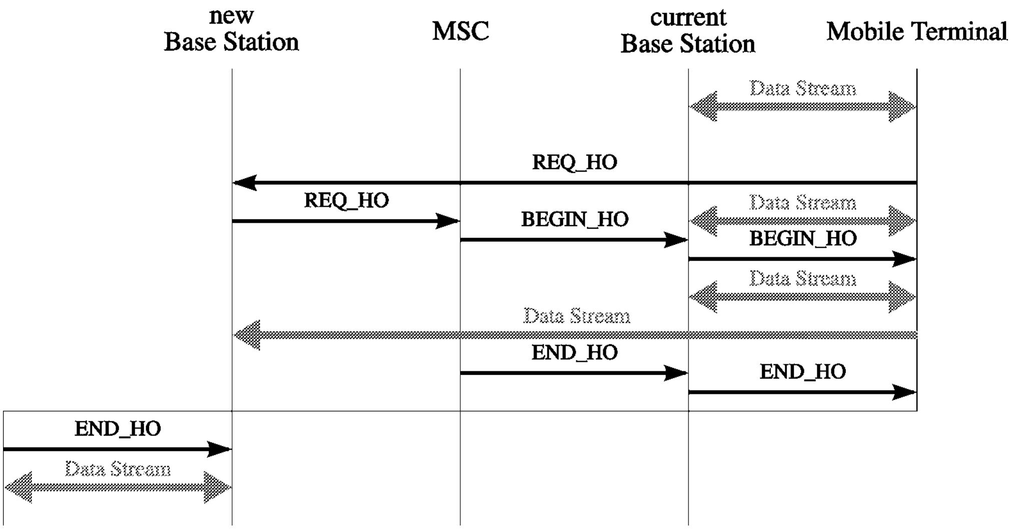


Figure 4. Message sequence chart of seamless handover.

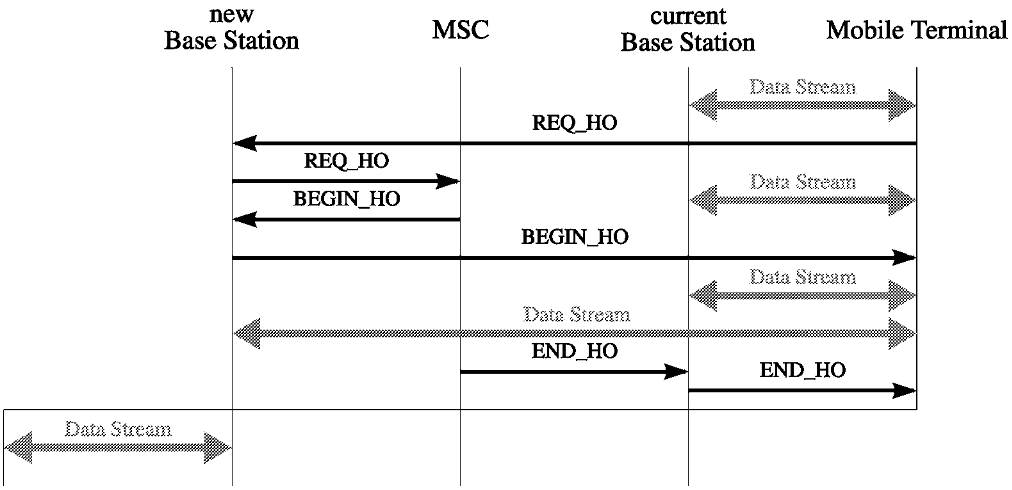


Figure 5. Message sequence chart of soft handover.

not taken into account acknowledgement and error-recovery mechanisms.

The handover information exchange along the old subpath is normally called *backward* or connected scheme (cf. [4,15]). If the MT first disrupts the connection, then seizes another radio channel towards the new BS and transfers handover signaling messages along this new route, the protocols belong to the class of *forward* or disconnected schemes. We do not consider the latter class in our study.

For all schemes we assume that first a connection-extension technique and then an incremental reestablishment of the new subpath after the completion of a handover are applied at the ATM VP- and VC-layers to reroute the cell streams to the MT along the new BS and to guarantee a smooth migration including the sequence integrity of cells (cf. [11,15,18]). Moreover, we expect that a handover-indication message initiates a segmentation of the ATM cell stream at the ATM, AAL or network layer of the MSC by the use of specific numbered flag cells or corresponding PDUs of higher layers following a flushing virtual-circuit concept (cf. [10,11]). Then misordering and cell loss during handover can be handled in a unique manner. Either a modified packet-level FEC approach or an appropriate retransmission protocol like ARQ selective repeat can be applied to cope with the corrupted segment of a message stream (cf. [3,7,19]).

## 3. Flow and congestion control of the ABR service class

Considering delay-insensitive non real-time services with severe loss constraints such as high-speed data communication, congestion and flow control are important traffic-management functions to maintain the efficiency of an ATM network and to guarantee the specific QoS requirements of each virtual connection of distinct users. Regarding the corresponding available bit-rate (ABR) service category, the ATM forum has specified a rate-based flow-control scheme in the traffic management (TM) specification 4.0 (cf. [1]).

The idea is to use the available bandwidth of a virtual path (VP) or link that is not consumed by those assigned VCCs of the CBR and VBR real-time service classes. To inform a

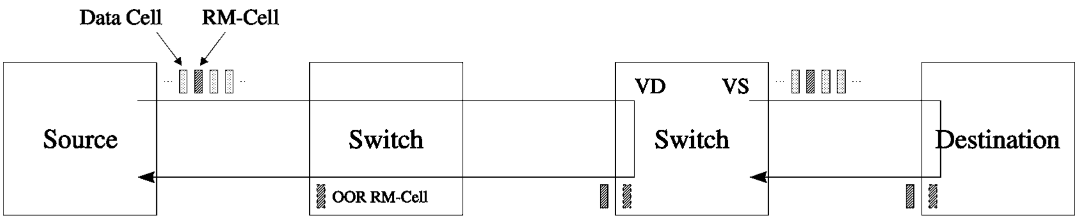


Figure 6. Explicit rate-based ABR flow-control with VS/VD control loops.

source of an ABR connection about the available bandwidth along its communication path, the source sends periodically resource management (RM) cells downward (FRM cells) to its destination. By this means the latter evaluates the congestion status determined by the queue lengths of the output buffers and the supported cell rate of the connection at each switch along the path and returns the RM cells (BRM cells) to the source (see figure 6, cf. [5]). On their way downward to the destination and backward to the source a switch along the path can specify explicitly the maximal supported cell transmission rate using the explicit rate (ER) field of an RM cell. For this purpose, it evaluates the bandwidth requirements of all assigned ABR connections, calculates a fair share of the available bandwidth and distributes it among all active ABR connections traversing the corresponding link. Following a backward explicit congestion notification concept, a congested switch or destination can furthermore send a controlled number (i.e. less than 10 cells per second) of own RM cells “out-of-rate” (OOR) without receiving an RM cell to speed up the notification of the source.

Receiving the congestion information in the ER field of the BRM cells, the source adapts its allowed cell rate (ACR) accordingly. The source starts sending with an initial cell rate (ICR) below its peak cell rate (PCR) specified at connection set-up. A minimum cell rate (MCR) is guaranteed for the connection. If in a wireless network the MCR cannot be preserved after a handover, a specific renegotiation procedure has to be used. It is implemented by a new `SOURCE_INFO` message for the source (cf. [20]). Here, we do not consider this concept, but we assume that a guarded channel scheme is applied to guarantee the minimal bandwidth after a handover (cf. [6]).

The explicit rate indication for congestion avoidance (ERICA) and its improved variant (ERICA+) are two of the most advanced rate-based congestion-control algorithms used in an ATM switch for the rate adaptation by RM cells (cf. [5]). Since ERICA is well know, details are not stated again (see [5]). We only stress that it is its goal to maintain the queue length at a very low level while guaranteeing a high target utilization $U$ of the used link. Regarding its improvement ERICA+ the varying transport capacity available for all ABR connections in the switch is estimated in a interval of prescribed length by the formula

$$\begin{aligned}&\text{ABR-capacity}\\&\quad = \text{link-capacity} - \text{CBR-capacity} - \text{VBR-capacity}.\end{aligned}$$

Taking into account the actual queueing delay $T_q$ at the output buffer of the switch, only a portion

$$\text{target-ABR-capacity} = f(T_q) \cdot \text{ABR-capacity}$$

of this capacity can be used by all assigned ABR connections. Given an upper bound

$$T_0 \leqslant \frac{(a-1) \cdot \text{QDLF}}{(a - \text{QDLF})}$$

on the delay, $T_0$ can be related to the desired queue length $Q_0$ without overload by $Q_0 = T_0 \cdot \text{ABR-capacity}$. The parameter QDLF (Queue Drain Limit Factor) prevents a dropping of the target-ABR-capacity to an unacceptable region and $a$ is a parameter. Then the used control function $f(T_q)$ is specified in terms of the observed queue length $q$ by (cf. [5])

$$f(T_q) = \begin{cases} \dfrac{bQ_0}{(b-1)q + Q_0} \in [b, 1], & 0 \leqslant q \leqslant Q_0, \\ \max\left(\dfrac{aQ_0}{(a-1)q + Q_0}, \text{QDLF}\right) & \\ \quad \in [1, \text{QDLF}], & q > Q_0, \end{cases} \tag{1}$$

with three parameters $a$, $b$, QDLF, e.g., $a = 1.15$, $b = 1.05$, $\text{QDLF} = 0.5$ (WAN)–0.80 (LAN). The ERICA+ algorithm operates at an optimal point with the prescribed delay $T_q = T_0$ and the queue length $q = Q_0$. It tries to guarantee 100% utilization at the ABR-capacity and a non-zero bounded queueing delay $Q_0$. This goal is achieved by the policy that a source can send with a higher rate until the desired queue length $Q_0$ is reached if the actual length $q$ is smaller than $Q_0$. The information about this temporary underloading is submitted by the BRM cells.

For each assigned active ABR connection feeding the output buffer towards a destination the switch first calculates a fair share using the target-ABR-capacity. By means of this fair share a new explicit rate is determined. Then the minimum of the target-ABR-capacity and this new rate is allocated to an outgoing RM cell. It overwrites the acutal ER value in the RM cell if it is lower than its current value.

At the beginning an ABR source starts sending with an initial cell rate (ICR). In our model it is determined by

$$\text{ICR} = \begin{cases} 0.1 \cdot \text{ER}, & z > 0.5,\ \text{MCR} = 0, \\ \text{MCR}, & z > 0.5,\ \text{MCR} > 0, \\ \text{ER}, & z \leqslant 0.5. \end{cases}$$

Here the load factor $z$ denotes the ratio of the total input rate of all ABR connections traversing a switch in a given direction and the ABR-capacity of the corresponding link (cf. [5]).

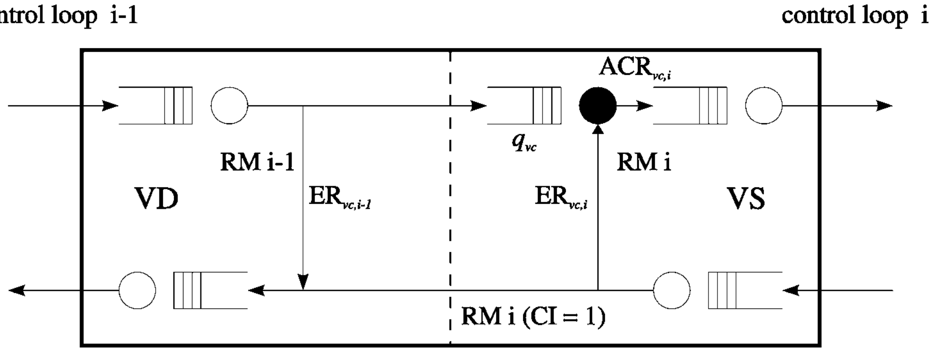


Figure 7. Structure of a VS/VD-switch.

The used initial value of the explicit rate ER is calculated according to the sketched procedure during the ABR connection set-up initiated by the MT. This scheme is used as basic control mechanism of a switch in our study.

The basic rate-based flow-control schemes for ABR connections use only one control loop spanning the path between the data source and the destination. However, in a WATM network it is advantageous to divide the control loop into several coupled smaller loops by introducing virtual sources (VS) and virtual destinations (VD), e.g., to separate the wireless and wired parts (see figure 6). Taking into account overload conditions determined by the queue-length processes in the switch buffers, the available bandwidth is distributed in a fair manner among all those competing active ABR conncetions sharing the same links and associated buffers of each control loop subject to the following contraints regarding the virtual sources and destinations (cf. [1]). Each control loop, apart from the first one, is fed by a virtual source. It behaves in the same manner as the original one. Received BRM cells are checked and removed. Each loop, apart from the last one, leads to a virtual destination behaving in the same manner as the original one. Received RM cells are processed and returned upstream as BRM cells to the associated virtual source. They are not sent downstream to the next loop. A switch with VS/VD-structure is shown in figure 7. The standard does not specify the coupling between two adjacent loops. The setting of others parameters is also network specific. In our model there exists a separate queue for each ABR connection vc in a VS/VD-switch (see figure 7). Let $q_{\text{vc}}$ denote the actual length of this queue and $n_{\text{vc}}$ be the prescribed number of data cells yielding an optimal utilization of the corresponding downstream VS-buffer of control loop $i$. $\text{ACR}_{\text{vc},i}$ is the associated allowed cell rate. Then we calculate the explicit rate $\text{ER}_{\text{vc},i-1}$ of the $i-1$ control loop by the formula $\text{ER}_{\text{vc},i-1} = f(T_{q_{\text{vc}}}) \cdot \text{ACR}_{\text{vc},i}$, where the function $f$ in (1) with $q_{\text{vc}}$ as $q$ and $n_{\text{vc}} = 50$ as $Q_0$ is used. The allowed cell rate of the $i-1$ control loop is computed by means of this new value $\text{ER}_{\text{vc},i-1}$. Additionally an OOR BRM cell is generated by the VD of the $i-1$ control loop if the VS of loop $i$ receives a BRM cell with congestion notification (CI $= 1$). Crossing the VS/VD boundaries, the MCR of a VCC should not be changed. This VS/VD approach has the advantage to improve the response of the controls subject to changing ABR capacity.

## 4. The performance of ABR flow-control protocols

In our simulation experiments performed for a client–server scenario in a WATM environment we study the efficiency of the ABR flow-control protocols ERICA and ERICA+ with the VS/VD concept. It is our main objective to evaluate the impact of different error-correction techniques of the wireless data link layer, i.e. ARQ selective repeat (SR) and forward error correction (FEC), as well as different handover schemes, i.e. hard, seamless and soft handover. FEC is normally used as reference scheme of the real-time background traffic in a WATM network to cope with the defective transport of ATM cells. In all switches we apply only FIFO queueing as scheduling procedure.

### *4.1. The WATM simulation model*

To enable a fair comparison of these combinations of the protocol functions, a generic simulation model and load scenario is used in all experiments. Figure 8 shows the model of the used WATM network scenario. For each link we depict its length and the transport capacity that can be used at the ATM layer by ABR connections at the start of the run as well as the available total transport capacity in paranthesis that can be used at the ATM layer above the physical and/or the wireless MAC layer by data connections and real-time background traffic. As medium access and control protocol a simplified version of TDMA/TDD is used (see figure 2, cf. [13]). The capacity is divided between up- and downlink in the ratio one to three since we model an asymmetric data transfer between mobile clients and a server in the wired network generating the ABR sources.

At the air interface between a terminal and the radio port (BTS) cell loss or cell corruption is caused by transmission or switching errors. We assume a BER of $10^{-4}$ and use a model generating independent errors. Cell losses due to the handover scheme are avoided by the latency of the handover protocol and buffering at the base stations. An MT waits until the downstream buffer of the old BS is empty before the old subpath is torn down and handover transition to the new BS is completed. Regarding ARQ-SR 1024 sequence numbers can be assigned to WATM cells of each ABR connection at the wireless link. This means that the window of the sender has a size of 511 cells. In the FEC scheme we use a

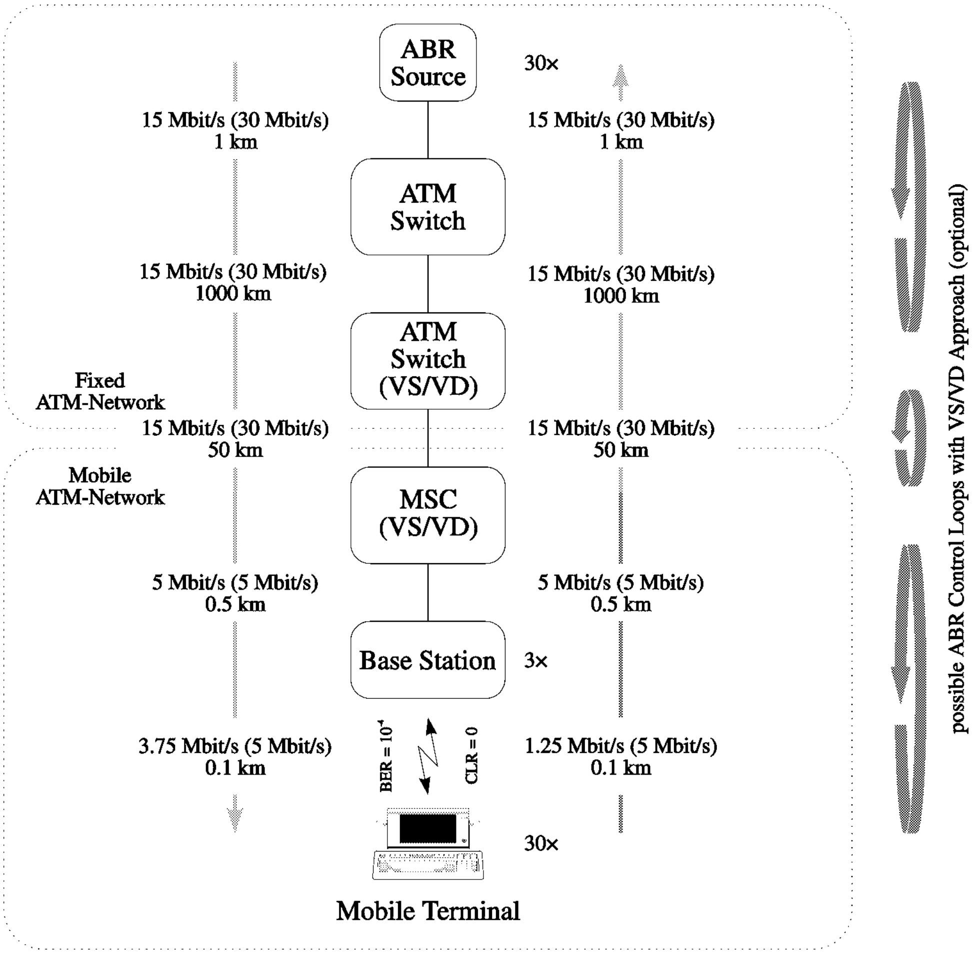


Figure 8. Architecture of the WATM simulation model.

$(511, 424)$-BCH code. It can correct up to 9 independent errors in the ATM PDU for a BER less than $10^{-3}$.

Regarding the link between the MSC and an arbitrary mobile terminal real-time traffic with variable holding time is used as background load. New connections of this traffic class are generated with a probability of $p_{\mathrm{bg}} = 0.25$ per second. Each connection consumes 5% of the downlink capacity as mean cell rate. The holding times are uniformly distributed between 5 and 30 s. These streams model the interference by the downstream slot allocation for CBR and VBR traffic at the MAC layer.

The ABR traffic load is generated by 30 mobile terminals divided into three groups of size 10. The terminals in each group transfer data with an MCR of 20, 30 and 40 ATM cells per second (cps). In a time interval of one second a terminal initiates the set-up of a new VCC from the server to the requesting MT with a probability of $p_{\mathrm{send}} = 0.20$. It instantiates an ABR source with a given MCR and a specified total load to be transferred downstream. After the successful data transfer the terminal can generate a new connection in the same manner.

In the wired part of the WATM network, there are 30 ABR sources instantiated by the terminals. They generate 12 VCCs to transmit a total load of 2500 cells, i.e. 117.1875 kbyte of user data, 12 VCCs with a load of 7500 cells (351.5625 kbyte) and 6 VCCs with 12500 cells as total payload (585.9375 kbyte). Each of these VCCs is statically assigned to a unique source–destination pair. This data transport emulates the transfer of web pages and files from a server. The network consists of 3 base stations. At the beginning in each coverage area of the base stations there are 10 mobile terminals, 4 have an MCR of 20, 4 an MCR of 30 and 2 an MCR of 40 cps. The probability of a handover request by an MT per second is given by $p_{\mathrm{ho}} = 0.1$. The new BS is selected at random.

Considering all three handover schemes a latency of 20 ms is assumed in the MSC for switching and rerouting operations from the old subpath to the new one connecting the MT and the MSC. In addition, both subpaths are maintained for further 10 ms in the seamless and soft handover scheme.

Considering the ABR flow-control protocol one resource management cell is inserted periodically after 31 user cells, i.e. $N_{\mathrm{RM}} = 32$ (cf. [1]). Regarding seamless handover an MT that receives an FRM cell along the old BS-MT link returns it as updated BRM cell along this old subpath as well as along the new one between the MSC and the BS reached during the transition phase. For soft handover FRM cells are sent together with the data along both subpaths and they are returned as BRM cells for the same ABR connection during

Table 1
Results of the simulation experiments with ERICA.

| Handoff | Error control | VS/VD | $q_{\max}$ | $E(q) = \bar{q}$ | conf($\bar{q}$) | Var($q$) | $N_{\mathrm{HO}}$ | $N_{\mathrm{OOR}}$ |
|---|---|---|---|---|---|---|---|---|
| Hard | FEC | no | 32 | 3.16 | ±0.09 | 4.47 | 922 | 1087 |
| | FEC | yes | 17 | 3.16 | ±0.09 | 4.30 | 971 | 234 |
| | ARQ | no | 42 | 4.06 | ±0.10 | 7.57 | 1047 | 10743 |
| Seamless | FEC | no | 32 | 3.21 | ±0.05 | 4.32 | 984 | 315 |
| | FEC | yes | 17 | 3.21 | ±0.06 | 4.20 | 932 | 91 |
| | ARQ | no | 42 | 4.00 | ±0.11 | 7.40 | 1040 | 9673 |
| Soft | FEC | no | 111 | 3.39 | ±0.13 | 11.45 | 931 | 4343 |
| | FEC | yes | 26 | 3.16 | ±0.09 | 4.57 | 945 | 2559 |
| | ARQ | no | 127 | 4.34 | ±0.10 | 12.66 | 1078 | 11966 |

Table 2
Results of the simulation experiments with ERICA+.

| Handoff | Error control | VS/VD | $q_{\max}$ | $E(q) = \bar{q}$ | conf($\bar{q}$) | Var($q$) | $N_{\mathrm{HO}}$ | $N_{\mathrm{OOR}}$ |
|---|---|---|---|---|---|---|---|---|
| Hard | FEC | no | 85 | 24.91 | ±0.63 | 134.09 | 968 | 112 |
| | FEC | yes | 70 | 24.88 | ±0.69 | 115.77 | 937 | 25 |
| | ARQ | no | 88 | 24.68 | ±0.80 | 146.18 | 940 | 420 |
| | ARQ | yes | 88 | 25.81 | ±0.65 | 126.08 | 926 | 85 |
| Seamless | FEC | no | 61 | 23.66 | ±0.74 | 134.33 | 957 | 11 |
| | FEC | yes | 55 | 24.42 | ±0.71 | 122.96 | 887 | 18 |
| | ARQ | no | 69 | 25.38 | ±0.69 | 144.72 | 967 | 43 |
| | ARQ | yes | 72 | 24.99 | ±0.56 | 123.97 | 1025 | 18 |
| Soft | FEC | no | 155 | 25.78 | ±0.68 | 148.11 | 872 | 1248 |
| | FEC | yes | 97 | 24.88 | ±0.73 | 129.26 | 918 | 514 |
| | ARQ | no | 155 | 25.98 | ±0.59 | 158.91 | 939 | 2284 |
| | ARQ | yes | 86 | 25.54 | ±0.74 | 132.85 | 975 | 769 |

the transition phase. In both cases the MSC calculates the minimum of the allowed cell rates by means of these BRM cells received from each subpath. It returns a received BRM cell with this new value to the corresponding source. Both in the new BS and the MSC the fair-share algorithm is applied to reallocate the assigned capacities among all ABR connections traversing this BS reached during the handover (cf. [5]).

Regarding ERICA the target utilization $U = 0.95$ of the link capacity is chosen in each switch. Regarding ERICA+ the parameters $a = 1.15$, $b = 1.05$, $T_0 = 0.005$ and QDLF $= 0.5$ are used. In ERICA+ the target operating points $Q_0 = 36.7$ for FEC and $Q_0 = 34.7$ for ARQ are used at the BS queues for the maximal ABR capacity achieved without the background load. Together with the available capacity for ABR connections two constants CBOUND, $T_0$ with CBOUND $= 2$ and $T_0 = 0.001$ for ERICA and $T_0 = 0.005$ for ERICA+ determine an upper bound $Q_c = \text{CBOUND} \cdot T_0 \cdot$ ABR-capacity on the queue length. It is used as a threshold triggering the emission of OOR-RM cells.

### *4.2. Performance evaluation of the protocols ERICA and ERICA+*

Applying FIFO queueing to ABR connections in the switches, we have first evaluated the performance of the flow-control protocol ERICA and then of ERICA+. It was our goal to analyze the queueing behavior at the MSC and BS downstream buffers as well as the response of the control schemes subject to the handover and error-control protocols. Using the sketched network scenario and the load model we performed various simulation runs of 10 minutes length each. The resulting outcome comprising the maximum $q_{\max}$, mean $E(q)$ and variance Var$(q)$ of the queue length processes $q$ in each base station as well as the 95% confidence intervals conf$(E(q))$ around the mean are listed in tables 1 and 2. Considering the three base stations we show only those results related to the base station with the maximal queue length during the whole run. We used a batch-means output analysis based on 10 subintervals. In each simulation period about 3.5 million cells are removed from each analyzed base station buffer and about 10 million cells are transferred downstream to all mobile terminals.

$N_{\mathrm{HO}}$ denotes the total number of handover requests performed during active connections of the run. $N_{\mathrm{OOR}}$ counts the total number of OOR-RM cells sent during the entire run by the three base stations as well as the MSC as an intermediate control point in the case of a VS/VD loop. A high number indicates severe overload situations.

The results shown in tables 1 and 2 indicate that both for ERICA and ERICA+ seamless handover performs best. This outcome is expected since the fast response of this scheme is guaranteed by sending BRM cells with recent information about the status of the wireless downlink between the new BS and the MT of a connection as soon as the MT can reach its new BS during a handover. The worst case in overloading the new BS buffer occurs if the ABR connection handed over to the corresponding BS-MT link and all running connections exceed the current ABR-capacity of this link. This means that

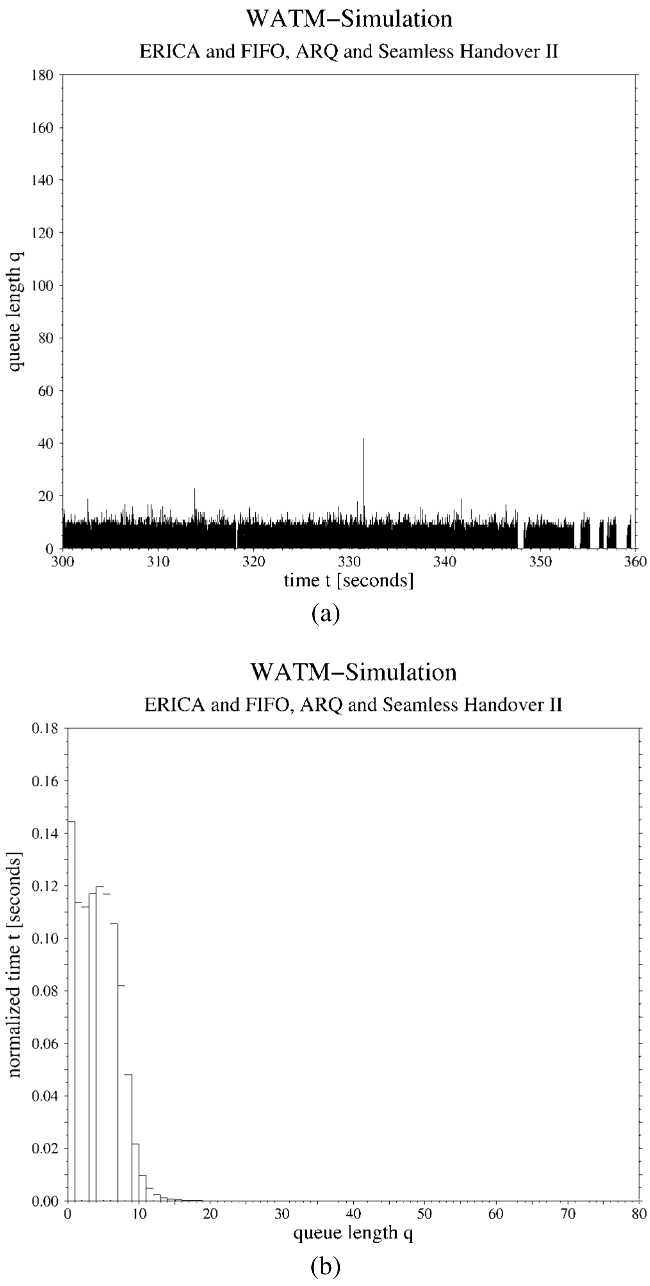


Figure 9. Queue length and histogram of ERICA run 6.

the source of this transferred connection sends too many cells as long as it is not informed about the new capacity bottleneck by a BRM cell from the new BS. Since a moving MT sends RM cells that it has received along the old BS-MT link upstream both along this old subpath and along the subpath of the new BS-MT link, the MSC can calculate the minimum of the rates allocated to both subpaths from the old and new BS and force the ABR source of the corresponding handover connection to adapt its ACR accordingly. Moreover, the existing ABR connections along the new BS-MT subpath are forced to update their allocated rates by means of the fair-share algorithm included in the ERICA and ERICA+ control schemes (cf. [5]). This fast response and the quick rebalancing of all ABR flows along the new BS reached after a handover request guarantee the stability of ABR flow control for the seamless handover scheme. They are the main reason for its superior queueing performance.

A hard handover requires the application of a VS/VD concept to provide satisfactory queueing performance. An alternative approach may be given by emulating the fast response of the seamless handover scheme, e.g., by using an enhanced MT-initiated backward handover scheme (cf. [15]). Further results of a current investigation show that the emission of OOR-RM cells from the new BS addressed during the handover by a request message provides a performance improvement (cf. [14]).

In all simulated scenarios a soft handover scheme does not work well. The additional loading of the downstream buffers of the new BS during handover is the reason of its degraded queueing performance. In the studied client–server service environment seamless handover shows that it is more reasonable to consider a handover from the reverse-link perspective of the MT as a temporary multicast connection. For this reason, additional loading of the downstream buffers by the handover scheme itself should be avoided if possible to cope in a better way with sudden overload surges by simultaneous handover events and error-correction requests.

For each run the two figures shown subsequently illustrate only that interval when the maximal queue length occurred as well as the histogram of the queue length process averaged over the whole run. The runs are numbered according to their positions in tables 1 and 2. The handover latency of the terminals are listed as well. The latter denotes the period when the mobile terminal sends a handover request until its completion.

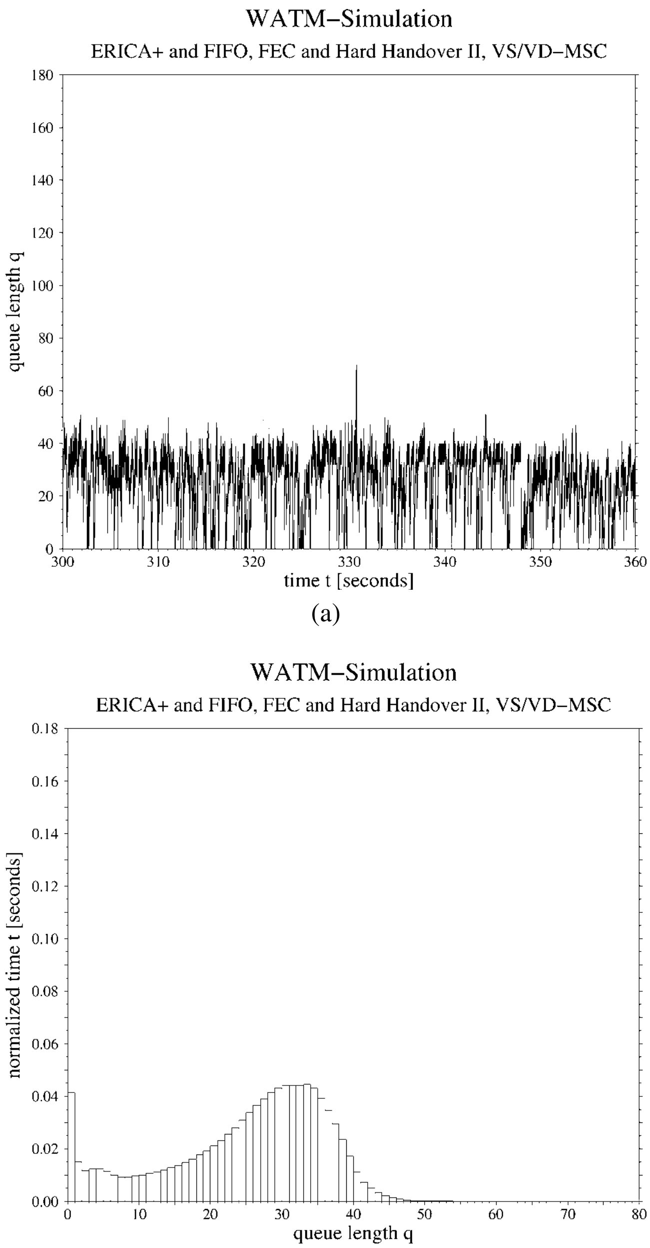
In run 6 of the experiment series related to the flow-control scheme ERICA ARQ and seamless handover yield a latency in the range of 32 ms to 56 ms for 1834 ABR connections (see figure 9). All base stations sent 9673 OOR-RM cells to control their moderately overloaded queues caused by 1040 handover requests.

Considering the ERICA scheme in more detail, the number of sent OOR-RM cells depends on the selected queue length bound

$$Q_c = \text{CBOUND} \cdot T_0 \cdot \text{ABR-capacity}$$

triggering the emission, e.g., CBOUND $= 2$, $T_0 = 0.001$ here. If its value is increased to reduce the OOR overhead, the quick response of the scheme is lost, particularly in the case of hard or soft handover. Considering seamless handover with ARQ a larger value can be chosen.

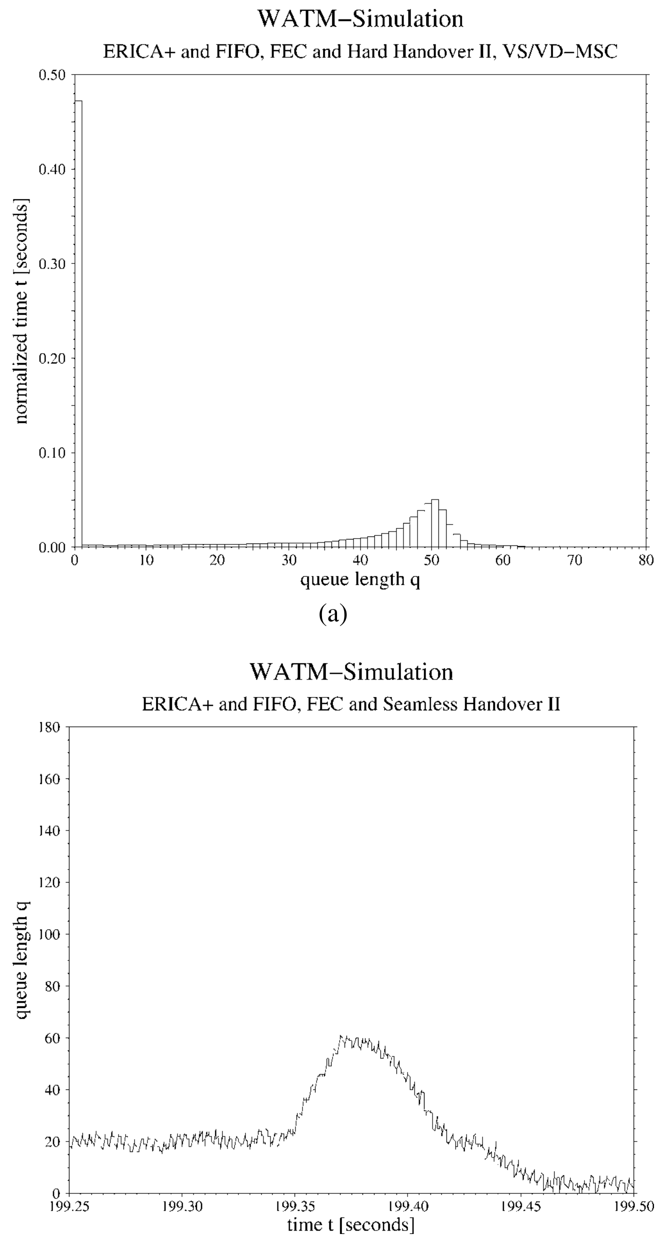
We now illustrate the outcome of the flow-control scheme ERICA+ in more detail. In run 2 FEC and hard handover with VS/VD at the MSC yield a latency in the range of 21 ms to 28 ms for 2044 ABR connections (see figure 10). Only 25 OOR-RM cells were sent by the MSC and all base stations to control their moderately loaded VS/VD queues caused by 937 handover events. In figure 11(a) we show the resulting behavior of a VC-specific queue in the MSC. The depicted queue length $q$ is the maximum among all those ABR connections traversing the MSC that are subject to two VS/VD flow-control loops spanning the ABR source and the MSC as well



(a)

(b)

Figure 10. Queue length and histogram of ERICA+ run 2.



(a)

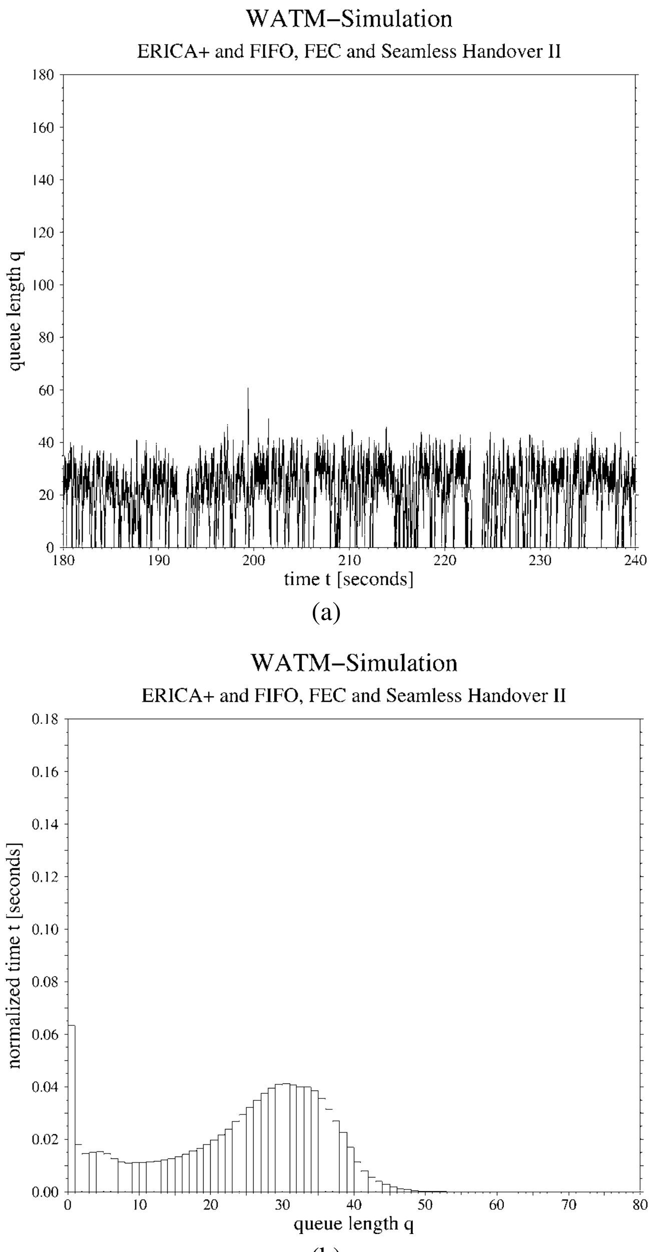
(b)

Figure 11. (a) Histogram of a VC-specific queue in the MSC in run 2 and (b) evolution of the queue length under overload in run 5.

as the latter and an MT. In the considered run the maximum $q_{\max} = 129$, the mean $E(q) = 30.97 \pm 2.44$ and the variance $\mathrm{Var}(q) = 442.14$ are observed in the MSC. In the MSC 56 ABR connections have consecutively used the considered VC-queue. Each generates a total load of 7500 cells and an MCR of 40 cps. The associated MT of these VC-connections has performed 35 handover requests during the evaluated run. The VD in the MSC has sent 5 OOR-RM cells to its ABR source to control the light overload of the queue. The histogram in figure 11(a) of the VC-specific queue illustrates that the actual length $q$ is very well controlled around the selected operating point of $n_{\mathrm{vc}} = 50$ cells.

In run 4 ARQ and hard handover with VS/VD at the MSC yield a latency in the range of 23 ms to 38 ms for 1923 ABR connections. A long cell-transport time due to several retransmissions of lost cells at a BS before handover completion and the policy to wait until the corresponding buffer is empty caused a maximal queue length $q_{\max} = 88$ in the downstream buffer of the BS reached after the handover. In all other base stations $q$ is in the range of 63 to 70. Moreover, the total number 85 of sent OOR-RM cells is moderate. The maximal queue length in the VS/VD-queues of the MSC is given by 127. We conclude that the combination of a VS/VD concept and ARQ is a useful policy regarding hard handover.

In run 5 FEC and seamless handover yield a latency in the range of 32 ms to 39 ms for 2027 ABR connections (see figure 12). Only 11 OOR-RM cells were issued by all base stations to control the light overload caused by 957 handover



(a)

(b)

Figure 12. Queue length and histogram of ERICA+ run 5.

requests. In figure 11(b) we show a typical evolution of the queue length of the new BS during a seamless handover in the relevant overload period [199.35, 199.42] in more detail.

In run 6 FEC and seamless handover with VS/VD at the MSC yield a latency in the range of 32 ms to 39 ms for 2007 ABR connections. The MSC and all base stations sent 18 OOR-RM cells to cope with the light overload only at the VS/VD queue of the MSC (not the base stations) caused by 887 handover requests.

In run 8 ARQ and seamless handover with VS/VD at the MSC yield a latency in the range of 34 ms to 49 ms for 1956 ABR connections. The maximal queue length $q_{\max} = 125$ is observed in the downstream buffer of the MSC.

The presented results show that, compared with ARQ, FEC can, of course, improve the queue length performance since retransmissions are prevented. But retransmission schemes are required to cope with a possible cell loss, duplication or misordering during the handover and transmission processes. Regarding seamless handover with the VS/VD concept ARQ provides, from our perspective, a feasible flow-control strategy whose performance comes close to the FEC strategy that is applied to the real-time background traffic. An interesting alternative to the retransmission of MAC PDUs is provided by a packet-level FEC scheme at the ATM AAL convergence sublayer. The latter is proposed to cope with the error recovery for multicast connections. Since a handover request can be considered as a temporary multicast connection, a packet-level FEC scheme applied in the MSC at the transport or network layer, the service-specific convergence sublayer of the AAL or even the ATM layer itself combined with a VS/VD scheme is a promising alternative.

## 5. Conclusions

In the paper we have considered high-speed data communication in a wireless ATM network using the ABR service class. By an object-oriented simulation model of a basic client–server scenario we have studied the performance impact of different error-recovery schemes and handover strategies. Our results reveal that a hard handover scheme generates a lot of resource management cells to control its overloaded buffers and that a soft handover scheme can cause a remarkable increase of the buffer contents in an ATM switch involved in the ABR flow-control schemes ERICA and ERICA+. A seamless handover strategy or a VS/VD-concept combined with a hard handover scheme can reduce these effects to a certain extent. The ABR flow-control procedures perform relatively well for a seamless handover scheme without applying the VS/VD concept to the loop spanned by the MSC or BS and a mobile terminal. Moreover, we have analyzed and compared the additional impact of different error-recovery mechanisms, i.e. ARQ selective repeat and FEC, applied at the wireless data link layer.

As consequence of our study, we propose to combine handover procedures, particularly seamless handover, and the emission of resource-management information in the ABR flow-control schemes. If hard handover is used, an early indication of the link status of the new BS-MT segment and the rerouting of the ABR connection should be supported by piggybacking the required congestion information in the handover request and acknowledgement messages.

Regarding wireless high-speed data communication in the uplink direction our experiments yield the conclusion that the ABR flow-control protocol should be modified to cope with error bursts experienced on the wireless links. If the channel conditions are systematically monitored and predicted, a link-awareness concept in a way similar to the TCP-Snoop protocol may improve the efficiency of ABR flow control.

In conclusion, the presented study analyzes the performance of the specified ABR service class with its basic flow-control protocols ERICA and ERICA+ for the high-speed data communication of a client–server scenario in a wireless ATM network. It points out a way to adapt the flow-control protocols to the new requirements of mobility management. Furthermore, it illustrates in accordance with recent studies (cf. [11]) that hard handover with a sophisticated zero-loss enforcement proposed so far for real-time connections may not be an adequate choice if a lightweight implementation of a versatile handover scheme for multimedia applications is required (cf. [20]).

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