The Impact of Handover Protocols on the Performance of ABR Flow-Control Algorithms in a Wireless ATM Network

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Abstract. Considering the high-speed data transfer by the ABR service class in a wireless ATM network, we investigate the impact of forward and backward hard handover protocols on the performance of the three rate-based ABR flow-control schemes Explicit Rate Indication for Congestion Avoidance (ERICA+), Fuzzy Explicit Rate Marking (FERM) and a new promising adaptation of FERM, called FERMA.

We evaluate the performance of these flow-control protocols by means of an object-oriented simulation model of a basic client-server architecture. Considering a standard hard handover protocol in a wireless ATM network, we show that our proposed enhanced signaling schemes based on a congestion-awareness concept and their integration into the ABR flow control have a positive influence on the stability and efficiency of the cell transfer by ABR connections. Moreover, we point out that the new adaptation of the fuzzy-control scheme FERM provides a promising alternative to the ERICA+ algorithm.

Keywords: wireless ATM network, handover protocols, rate-based ABR flow control, fuzzy control.

1 INTRODUCTION

In the last decade, enormous technical efforts have been made to develop a platform enabling the integration of voice, data and multi-media communication. The Asynchronous Transfer Mode (ATM) provides one approach that looks very promising from the perspective of traffic engineering. Recently, however, there is the popular belief that the Internet paradigm will dominate the end-to-end communication of advanced endsystems. Nevertheless, there is still interest in the development of ATM, at least as the underlying technology of a high-speed backbone network. Moreover, it is obvious that several lessons learned during ATM studies may be transferred successfully to the Internet world. Regarding the wireless access to such high-speed networks an improved mobility support is required. In this respect, the provision of an efficient wired and wireless access to an ATM backbone network is a challenging technical and economic issue (cf. [1], [2]).

In this paper we consider high-speed data communication in a wireless ATM (WATM) network. For this purpose, we use the ABR service class that is specified in the ATM forum document Traffic Management Specification 4.0 (cf. [3]). 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. [4], [5], [6]). It includes a simplified version of the TDMA/TDD structure and the associated wireless MAC protocol of this system.

Using an object-oriented discrete event simulation model of a basic client-server scenario in a wireless ATM network (see figure 1), we study the impact of the error-prone wireless communication channel and of mobility-management techniques determined by backward and forward hard handover protocols (cf. [4], [7], [8], [9], [10]) on the performance, i.e. efficiency, robustness and fairness, of the rate-based ABR flow-control algorithms ERICA+, FERM and our FERM-adaptation.

The rest of the paper is organized as follows. Section 2 sketches the basic principles of rate-based ABR flow-

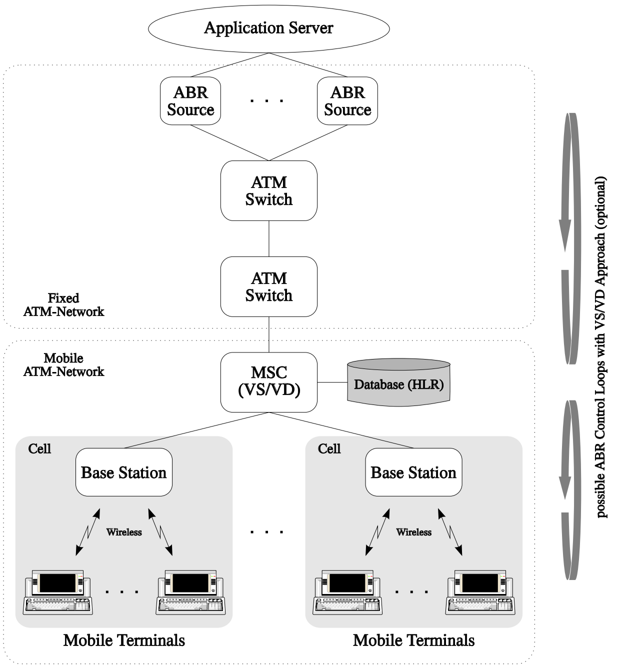

Figure 1: Structure of a generic WATM network scenario

control algorithms and the optional virtual source/virtual destination (VS/VD) approach, i.e. an ABR connection is split into two or more segments. Furthermore, we discuss the main ideas of fuzzy logical methods and of the original FERM algorithm. Then we describe our adaptation of the FERM algorithm to a WATM environment. In section 3 the used improved backward and the forward handover protocol are described. The simulation model and the results obtained by the performance analysis of the three considered ABR flow-control algorithms are presented in section 4. Finally, some conclusions are drawn in section 5.

2 RATE-BASED ABR FLOW-CONTROL ALGORITHMS

The ATM Forum has specified three important service classes for the use in an ATM network: constant bit rate (CBR), variable bit rate (VBR) and available bit rate (ABR) (cf. [3]). Connections of the ABR service class are designed to use the remaining capacity of an ATM network after the CBR and VBR service-class connections have received their current cell rate. To avoid congestion in an ATM network and to use the whole capacity efficiently, the source of every ABR connection has to be informed regularly about this remaining capacity. For this purpose, the ATM Forum has standardized rate-based ABR flow-control algorithms.

2.1 BASIC PRINCIPLES

In a rate-based ABR flow-control algorithm every source of an ABR connection sends periodically, i.e. after $N_{\text{RM}} - 1$ user cells, a resource management (RM) cell to its destination. This RM cell includes an explicit rate (ER) which is set by the source to the maximal allowed sending rate, called peak cell rate (PCR), and the current cell rate (CCR) of the source. The destination returns this RM cell to the source. On the path from the destination to the source due to actuality every switch regularly calculates an internal ER value depending on the ABR link cell rate and the number of active ABR connections with their QoS parameters. This switch-internal ER is compared to the ER in the incoming RM cell. If the internal ER value is smaller than the ER in the RM cell, the latter is replaced by the internal ER. Finally, the source receives the RM cell and sets its allowed cell rate (ACR) to the ER in the RM cell which is the minimum of all switch-internal ERs on the path through the ATM network. For an ABR source the ATM network can permit a minimum cell rate (MCR) greater than zero. In this case the MCR is the lower bound of the ACR, i.e. $0 \leq \text{MCR} \leq \text{ACR} \leq \text{PCR}$.

If a switch is congested, it can create a temporally limited number of own RM cells, called out-of-rate (OOR-)RM cells, and send them together with the current internal ER value to the related ABR sources. The idea is to inform these ABR sources much faster about the congestion than it is possible by normal in-rate RM cells.

The basic rate-based flow control for an ABR connection uses only one control loop spanning the path between the source and the destination. Regarding WATM networks it is advantageous to divide the control loop into several coupled smaller loops by introducing virtual sources (VS) and virtual destinations (VD) in some switches between the source and the destination, e.g. to separate the wired and wireless parts of the network. The standard does not specify the coupling between two adjacent control loops. It is only mentioned that the QoS parameters, e.g. PCR and MCR, of a splitted ABR connection should be the same in each control loop. The VS/VD-approach has the advantage to decrease the response time of the virtual sources under changing ABR capacity.

The rate-based flow control of the ABR service class in wired ATM networks has been the topic of many studies, since the internal calculation of the explicit rate in a switch depends on the selected rate-based flow-control scheme, e.g. the explicit rate indication for congestion avoidance (ERICA) or its improvement ERICA+ (cf. [11]).

2.2 ERICA/ERICA+

Since ERICA and ERICA+ are well know, details are not stated again. The main goal of ERICA is to control the ABR queue length q at a very low level while maintaining an eligible high target utilization $U = 1 - \varepsilon$, $\varepsilon > 0$, of the ABR link cell rate, i.e. the ABR target cell rate TCR can be calculated by:

$$\text{TCR} = U \cdot \text{ABR link cell rate} \tag{1}$$

In addition, ERICA+ considers the current ABR queueing delay t or the corresponding queue length q of an ATM-switch and calculates the ABR target cell rate TCR by

$$\text{TCR} = f(q) \cdot \text{ABR link cell rate} \tag{2}$$

e.g. with $f(q) \in [1.05, \ldots, 1, \ldots 0.5]$ for $q \in [0, \ldots, q_0, \ldots, \infty[$. ERICA+ operates at an optimal working point with a target utilization of one and a fixed queueing delay t_0 or the corresponding queue length q_0 greater than zero.

Both flow-control algorithms calculate a fair share

$$\text{FS} = \frac{\text{TCR}}{N_{\text{ABR}}} \tag{3}$$

whereby $N_{\text{ABR}} > 0$ is the number of active ABR connections traversing the switch. Finally, the switch-internal explicit rate of an ABR connection is a combined calculation of the fair share, the periodically measured load factor

$$z = \frac{\text{incoming ABR cell rate}}{\text{TCR}} \tag{4}$$

of the switch and the current cell rate (CCR) of the active ABR connections.

Apart from ERICA and ERICA+ there are many other rate-based congestion-avoidance schemes of interest. One of them is the fuzzy explicit rate marking (FERM, cf. [12]) which is described in the following subsection.

2.3 FUZZY LOGIC AND FERM

The most important part of a fuzzy control system is the fuzzy logic controller (FLC, cf. [12]). With the FLC the human train of thoughts can be adapted in a simple way by using linguistic variables with their set of linguistic values and a small number of linguistic rules or relational expressions. One of the linguistic rules in the nonlinear FERM fuzzy congestion controller (FCC) is for example (see appendix):

If the buffer (length) is full and
the rate of change is increasing fast, (R11)
then the flow rate should be very little.

"buffer (length)", *"rate of change"* and *"flow rate"* are called linguistic variables and *"full"*, *"increasing fast"* and *"very little"* are examples of their valid linguistic values.

The design of a FLC is split into two parts: First, the linguistic rules are set ("surface structure") and then the membership functions of the linguistic variables are determined ("deep structure"), quite often by a more intuitive and pragmatic choice.

Dependent on the input parameter x the membership function m_V of a linguistic variable V denotes the weights $w_{v_k} \in [0,1]$ of the valid linguistic values v_k, $1 \le k \le n_V$, i.e.:

$$m_V(x) = (w_{v_1}, \ldots, w_{v_{n_V}}) \in [0,1]^{n_V} \tag{5}$$

Here each membership function m_V is represented by a composition of n_V membership functions of the fuzzy sets F_{v_k} of its corresponding linguistic values v_k, i.e.

$$\begin{aligned} m_V(x) &= m_{v_1}(x) \otimes \ldots \otimes m_{v_{n_V}}(x) \\ &= (w_{v_1}, \ldots, w_{v_{n_V}}) \end{aligned} \tag{6}$$

with the tensor operator $\otimes$. Let $\oplus$ denote the s-norm operator $\max$. For an FLC with a single output variable Y with the membership function $m_Y(y) = m_{y_1}(y) \otimes \ldots \otimes m_{y_{n_Y}}(y)$ its weighted membership function

$$\begin{aligned} m_Y^*(y) &= w_{y_1} \cdot m_{y_1}(y) \oplus \ldots \oplus \\ &\quad\; w_{y_{n_Y}} \cdot m_{y_{n_Y}}(y) \end{aligned} \tag{7}$$

represents the outcome of the L related fuzzy rules $v^{(l,1)} \times \ldots \times v^{(l,n)} \to y^{(l)}$, $1 \le l \le L$, with n linguistic values $v^{(l,1)}, \ldots, v^{(l,n)}$ of n linguistic variables $V^{(1)}, \ldots, V^{(n)}$ and their weights $w^{(l,1)}, \ldots, w^{(l,n)}$, dependent on the input-value vector $(x_1, \ldots, x_n)$ of the FLC, i.e. for $1 \le l \le L$, $1 \le j \le n$ and exactly one k, $1 \le k \le n_{V^{(j)}}$, it holds:

$$\begin{aligned} v^{(l,j)} &= v_k^{(j)} \\ w^{(l,j)} &= w_{v_k^{(j)}} = m_{v_k^{(j)}}(x_j) \end{aligned} \tag{8}$$

If none of the linguistic values $v^{(l,j)}$ of a linguistic variable $V^{(j)}$ are used in a linguistic rule l, i.e. the linguistic rule l is independent of $V^{(j)}$, then $w^{(l,j)}$ is set to 1.

Applying the often used norms $\min$ and $\max$ the weights w_{y_k}, $1 \le k \le n_Y$, of Y can be expressed by:

$$w_{y_k} = \max_{y^{(l)} = y_k} \{\min\{w^{(l,1)}, \ldots, w^{(l,n)}\}\} \tag{9}$$

The weights of all linguistic values of the linguistic variables are used to determine the demanded fuzzy value by a weighted analysis of the linguistic rules with a fuzzy inference engine. Due to computational simplicity the membership function of a linguistic variable is often triangular or trapezoidal shaped (see figures 2 – 6 and appendix).

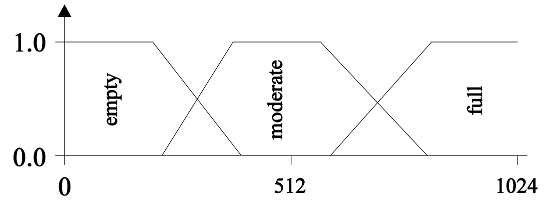

Figure 2: Membership function of the average queue length $\overline{q}$ of FERM

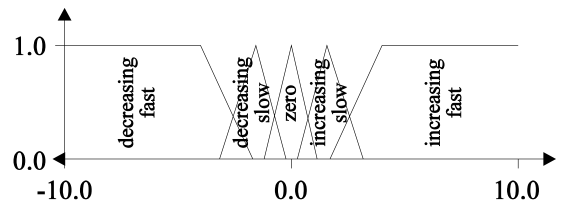

Figure 3: Membership function of the fractional queue growth rate Δg of FERM

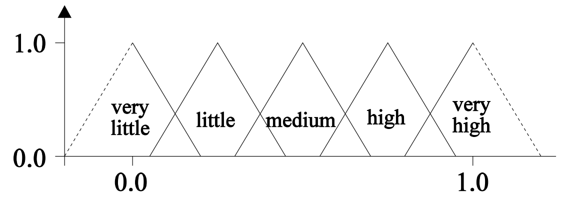

Figure 4: Membership function of the fractional flow rate Δf of FERM

For every control interval i with the duration of $N = 50$ cell times the FERM algorithm in the ATM switch monitors the average ABR queue length $\overline{q}(i)$ and its growth rate $g(i) = \overline{q}(i) - \overline{q}(i-1)$ or its fractional growth rate $\Delta g(i) = g(i)/N$, respectively, for a buffer with a maximal size of 1024 ABR cells. For all sources with ABR connections traversing the considered ATM switch these two parameters are used by the FCC to compute the fractional flow rate $\Delta f = f(\overline{q}, g) \in [0, 1]$ and the ABR target cell rate TCR given by:

$$\text{TCR} = f(\overline{q}, g) \cdot \text{ABR link cell rate} \qquad (10)$$

For these ABR connections the fair share FS (see (3)) determines the switch-internal explicit rate.

The FCC described in [12] uses three linguistic values (*"empty"*, *"moderate"*, *"full"*) for the average queue length $\overline{q}$ (*"buffer (length)"*), five linguistic values (*"decreasing fast"*, *"decreasing slow"*, *"zero"*, *"increasing slow"*, *"increasing fast"*) for the queue growth rate g (*"rate of change"*) and eleven linguistic rules to compute the weights of the linguistic values (*"very little"*, *"little"*, *"medium"*, *"high"*, *"very high"*) of the fractional flow rate Δf. Then the fractional flow rate Δf itself and after that the ABR target cell rate TCR (*"flow rate"*) are computed by (10).

Before every control interval i the weights of all linguistic values are set to 0. Then the weights $w_{\overline{q}_k}$, $1 \leq k \leq 3$, of the average queue length $\overline{q}(i)$ and the weights w_{g_k}, $1 \leq k \leq 5$, of the queue growth rate $g(i)$ are determined. For the linguistic rule (R11), for instance, the last step of the computation can be expressed by (see (9)):

$$w_{\Delta f_1} = \max\{w_{\Delta f_1}, \min\{w_{\overline{q}_3}, w_{g_5}\}\} \qquad (11)$$

There may be other linguistic rules which have an influence on $w_{\Delta f_1}$. By the weights $w_{\Delta f_k}$, $1 \leq k \leq 5$, the membership function $m_{\Delta f}$ of Δf is converted to $m^*_{\Delta f}$ (see (7)). The weighted linguistic values of Δf are combined by a special fuzzy calculation, called center of gravity (COG), to the new fractional flow rate Δf (cf. [12]):

$$\Delta f = \frac{\int y \cdot m^*_{\Delta f}(y)\, dy}{\int m^*_{\Delta f}(y)\, dy} \qquad (12)$$

Since the membership function $m_{\Delta f}$ of Δf has in this case the same symmetrical shape for every linguistic value of Δf and equal distances between them, (12) can be transformed into

$$\Delta f = \frac{\sum_{k=1}^{5} w_{\Delta f_k} \cdot \Delta f_k}{\sum_{k=1}^{5} w_{\Delta f_k}} \qquad (13)$$

for a simplified computation with $\Delta f_1 = 0.00$, $\Delta f_2 = 0.25$, $\Delta f_3 = 0.50$, $\Delta f_4 = 0.75$ and $\Delta f_5 = 1.00$.

In a real ATM switch there is no need for a complex and computational intensive fuzzy inference engine in the FLC. After the linguistic rules are found and the linguistic values are tuned by a simulator the control surface is known and can be stored as a lookup table requiring only a few kilobytes of read-only memory (ROM). In combination with a simple interpolation algorithm FERM can be implemented in such a way with a very fast response time.

In [12] the fairness of FERM is demonstrated, at least in a max-min sense. It is remarkable that this fairness is achieved by using only local information in the switch.

2.4 ADAPTATION OF FERM

In [13] we have studied the influence of different handover protocols on the performance of the ABR flow-control algorithm ERICA+. The results reveal that performance improvements may be achieved if the used flow-control protocol adapts faster to changing buffer loads caused by handovers of mobile terminals. For this reason, we have adapted the original FERM algorithm in [12].

The goal is to achieve a fixed queueing delay $t_0 > 0$ with a related target queue length $q_0 > 0$ similar to ERICA+. Therefore, we have inserted two new linguistic values *"short"* and *"long"* for the linguistic variable *"buffer (length)"* (see figure 5) and ten $(= 2 \cdot n_g)$ additional linguistic rules to control the queue length q more precisely. Furthermore, the original linguistic rule (R7) of FERM has been changed (see appendix).

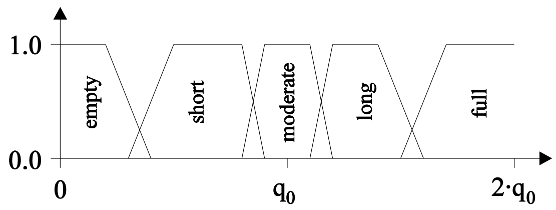

Figure 5: Membership function of the queue length q of FERMA

For example, one of our new linguistic rules to achieve these goals is the following (see appendix):

If the buffer (length) is long and the
rate of change is decreasing slow, (R18)
then the flow rate should be medium.

The time of the control interval of our adaptation is set to the mean arrival time of $N = 50$ ABR cells. In every control interval i we consider the current queue length $q(i)$ and its growth rate $g(i) = q(i) - q(i-1)$ or its fractional growth rate $\Delta g(i) = g(i)/N$, respectively.

The input range of the membership function of the fractional growth rate Δg (see figure 6) has been changed to substantial lower values because of the chosen target queue length $q_0 < N \ll 512$ at each base station (BS) in our WATM network.

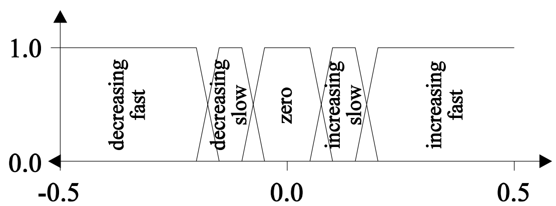

Figure 6: Membership function of the fractional queue growth rate Δg of FERMA

As in the original FERM algorithm in our FERM-adaptation the fractional flow rate Δf is a linguistic variable with a simplified membership function, i.e. only the weights of the linguistic values of Δf are considered. The values $\Delta f_1 = 0.90$, $\Delta f_2 = 0.95$, $\Delta f_3 = 1.00$, $\Delta f_4 = 1.02$ and $\Delta f_5 = 1.05$ are selected to achieve a moderate queue length q in the neighbourhood of q_0. Note that no normalization of the membership function $m_{\Delta f}$ is performed here to simplify the computational scheme.

Moreover, we choose a different formula to calculate the weights of the linguistic values of Δf. The new linguistic rule (R18), for instance, can be computationally expressed by:

$$w_{\Delta f_3} = w_{\Delta f_3} + w_{q_4} \cdot w_{g_2} \tag{14}$$

There may be other linguistic rules which have an influence on $w_{\Delta f_3}$, too. Then the new fractional flow rate Δf can be calculated by (13).

If an ATM switch is congested, i.e. if the queue length q exceeds an upper bound $2 \cdot q_0$, the fractional flow rate has to be reduced to a value distinctly lower than one.

Similar to the original FERM algorithm the switch-internal explicit rate for the ABR connections through the switch is the fair share FS (see (3)).

For the FERM-adaptation the described membership functions of the linguistic variables (see appendix) and the values of the fractional flow rate are the result of a more intuitive and pragmatic choice and not of an analytic approach. Nevertheless, this selection provides promising results.

Since there is no change in the bandwidth allocation among the ABR connections the fairness of our FERM-adaptation is comparable to the fairness of the original FERM algorithm.

3 HANDOVER PROTOCOLS

Regarding data communication by the ABR service class in a WATM network the connections must be permanently maintained during the communication phase since a mobile terminal (MT) moves within a certain coverage area of a base station (BS) and may cross its boundary. In this case, the connections must be handed over to a new transmission cell whereby a new radio channel is seized and the QoS requirements of the corresponding virtual channel connections (VCCs) must be satisfied in addition to the existing ones within the new cell. The corresponding hard handover protocol has to guarantee the sequence integrity and loss-free delivery of the ATM cells during this transition process. Moreover, interworking with the rate-based ABR flow-control algorithms is required to guarantee the effectiveness of the approach.

To achieve these goals, we have developed an improved backward hard handover protocol for handoffs between the transmission cells of the current BS (CBS) and a new BS (NBS) of the MT, called better hard handover (see figures 7 and 8 for a simplified error- and loss-free message transfer without acknowledgments).

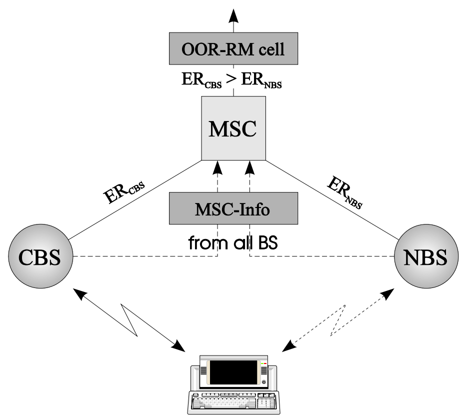

Figure 7: MSC information-message transfer of better hard handover

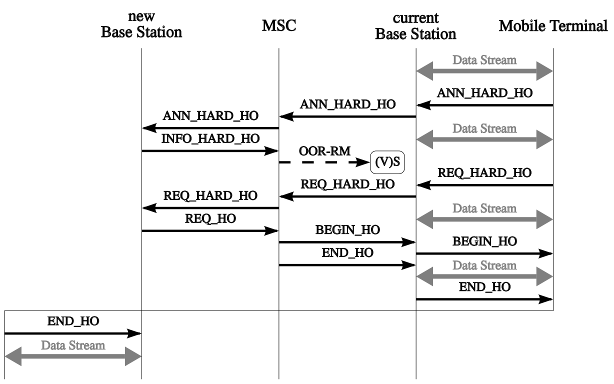

Figure 8: Simplified message transfer of backward better hard handover

Derived from a congestion-awareness concept our handover protocol is a minimal enhancement of a standard hard handover protocol. It includes only a few new signaling messages using special RM cells. Independent of handover events they are exchanged between the base stations and the mobile switching center (MSC) which is an ATM switch with mobility support extensions for the wireless part of the network.

Whenever there is a substantial change of the ABR bandwidth or an alteration in the number of active ABR connections in the transmission area of a BS the BS informs the MSC immediately by sending an MSC information message with the current ABR target cell rate TCR, the number of ABR connections and the sum of their minimum cell rates. This very low additional bandwidth requirement in the path between each BS and the MSC gives the MSC the knowledge about the current possible ER in each BS transmission area.

The improved backward hard handover is combined with forward handover as a fallback procedure in the case of a too short announcement period before a handover. This means that normally every mobile terminal announces its expected new handover t_a milliseconds before the real handover event occurs. If there is not enough time for such an announcement, the mobile terminal has to perform a forward handover (see figure 9, cf. [13]).

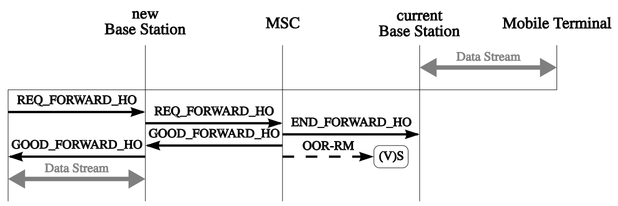

Figure 9: Simplified message transfer of forward better hard handover

If the MSC receives the response `INFO_HARD_HO` to a backward handover announcement `ANN_HARD_HO` from an NBS or a forward handover request `REQ_FORWARD_HO` it sends an OOR-RM cell to the (virtual) source of the ABR connection if $\mathrm{ER}_{\mathrm{CBS}} > \mathrm{ER}_{\mathrm{NBS}}$.

After the announcement and before the end of a backward hard handover the MSC calculates the ER of the related ABR connection as the minimum of $\mathrm{ER}_{\mathrm{CBS}}$, $\mathrm{ER}_{\mathrm{NBS}}$ and the MSC-internal value $\mathrm{ER}_{\mathrm{MSC}}$.

To avoid ABR cell transmissions from the current base station to the new base station of a moving mobile terminal or ABR cell losses caused by a forward handover the MSC stores the last S consecutive segments of the cell stream of every active ABR connection. Each segment comprises $N_{\mathrm{RM}} - 1$ user cells and one RM cell, i.e. at most $S \cdot N_{\mathrm{RM}}$ cells are stored for each active ABR connection at the MSC. If a mobile terminal performs a forward handover it requests the required segments in addition. If these segments are still stored in the MSC the latter can successfully complete the forward handover by sending the `GOOD_FORWARD_HO` message to the mobile terminal. Otherwise some cells are lost and the MSC sends the `BAD_FORWARD_HO` message to the mobile terminal which invokes an error-recovery mechanism. The latter case can be avoided by a reasonable setting of the parameter S.

It is the main advantage of our new hard handover protocol that in the period between the announcement and the start of the handover process the source of the moving mobile terminal can be informed about the ER over the new BS and it can reduce its CCR if it is necessary. By these means, congestion in the new BS caused by simultaneous hard handover events can be avoided (cf. [13]).

4 PERFORMANCE EVALUATION

4.1 WATM SIMULATION MODEL

In this section, we give a concise description of our wireless ATM (WATM) simulation scenario for the performance evaluation of the considered ABR flow-control algorithms. For further details the reader is referred to [13].

The basic structure of our WATM simulation model consists of one mobile switching center (MSC) and three base stations (BSs) connected to the MSC (see figure 10).

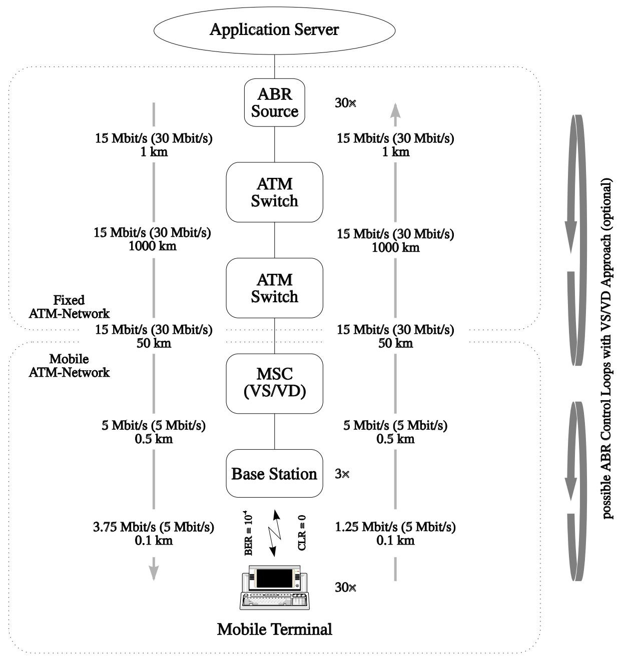

Figure 10: WATM simulation scenario

Thirty mobile terminals (MTs) move around in the coverage area of the WATM network. In an interval of one second there are given probabilities $p_{send} = 0.2$ and $p_{ho} = 0.1$ for the initiation of an ABR connection with a total load of 2500, 7500 or 12500 ABR cells from a server downlink to a client running in an MT and for a handover of an MT from the current BS (CBS) to a randomly selected new BS (NBS). In this case, the conditional probability of a forward handover is given by $p_{fho} = 0.2$.

Considering figure 10, for each link in the fixed part of the network the first bandwidth value represents the ABR bandwidth at the beginning of a simulation run and the second one (in parenthesis) represents the whole bandwidth of the link. In the mobile part of the network the ABR bandwidth is equal to the whole bandwidth of the link at the beginning of a run. In general, the downlink connections (BS $\rightarrow$ MT) require much more bandwidth than the uplink connections (MT $\rightarrow$ BS). Therefore, the whole bandwidth in the radio link is split up into a ratio of 3 to 1 for the down- and the uplink directions. During a simulation run the ABR bandwidth between the MTs and the MSC is variable due to changing high-priority CBR or VBR background traffic load in the network.

In the radio link the transmission protocol is time division multiple access with time division duplex (TDMA/TDD). It is combined with selective repeat automatic repeat request (SR-ARQ) as error-recovery protocol.

Furthermore, in the radio link of each base station a bit error rate (BER) and an a priori cell loss rate (CLR) are defined. In the performed simulation runs of the considered ABR flow-control protocols we have used three different initial BERs (10^{-3}, $5 \cdot 10^{-4}$, 10^{-4}) in the three base station transmission areas. During a run the BER will be changed dynamically in the range of at most ± 10 % and for a random duration. A simple Gilbert-Elliott error model with two states called good (G) and bad (B) is used to model the characteristics of those correlated and bursty bit errors at a real physical link that cannot be overcome by error-correction techniques and cause cell transmission errors (see figure 11).

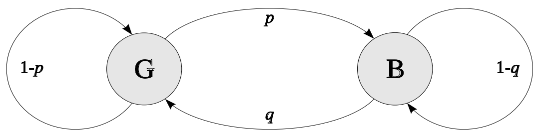

Figure 11: Gilbert-Elliott error model (GEEM)

The state transition probabilities p and q are calculated by the equations (cf. [14]):

$$p = \frac{\mathrm{BER}}{(1 - \mathrm{BER}) \cdot \mathrm{E(B)}} \qquad q = \frac{1}{\mathrm{E(B)}} \tag{15}$$

Here $\mathrm{E(B)}$ is the mean number of bits in an error burst. In the special case $p + q = 1$ the same error model describes a radio link with non-correlated bit errors, i.e. $p = \mathrm{BER}$ and $q = 1 - \mathrm{BER}$.

All other parameter settings in the WATM simulation model, e.g. $N_{\mathrm{RM}} = 32$, $S = 5$ and $t_a = 10$, are equal to our previous experiments (cf. [13]).

For FERM the maximal buffer size is set to the congestion bound of ERICA+ and FERMA given by $2 \cdot q_0$.

The control loop spanning the source which is instantiated by a server in the wired network and the destination at a mobile client can be split up at the MSC by using the virtual source/virtual destination (VS/VD) approach of the ABR flow-control protocol (cf. [3]). This approach is also considered in this paper to improve the response of the control loop.

4.2 PERFORMANCE ANALYSIS

We have performed each simulation run for 600 seconds. During this time more than 10 million ABR cells are transferred downstream to the mobile terminals. In the following tables 1, 2 the results of the runs are listed.

Table 1: Results for ABR flow control

	ERICA+	FERM	FERMA
$q_{\max}$	162	107	145
$\overline{q}$	25.96	4.75	26.82
cf($\overline{q}$)	$\pm\,0.71$	$\pm\,0.11$	$\pm\,0.89$
$\sigma^2(q)$	147.12	20.75	151.34
N_{HO}	805 (218)	859 (208)	799 (199)
N_{OOR}	1055 (451)	96 (460)	957 (392)

Table 2: Results for VS/VD ABR flow control

	ERICA+	FERM	FERMA
$q_{\max}$	141	80	123
$\overline{q}$	25.15	4.22	26.83
cf($\overline{q}$)	$\pm\,0.71$	$\pm\,0.11$	$\pm\,0.71$
$\sigma^2(q)$	125.79	13.12	139.85
N_{HO}	822 (217)	880 (229)	808 (189)
N_{OOR}	629 (464)	29 (466)	609 (422)

The maximal queue length $q_{\max}$, the mean queue length $\overline{q}$, the 95 % confidence interval cf($\overline{q}$) around $\overline{q}$ calculated by batch-means and the variance $\sigma^2(q)$ of the queue length q are shown only for the base station with the highest maximal queue length $q_{\max}$ during the simulation run.

N_{HO} denotes the total number of performed backward handovers and in parenthesis the total number of performed (good) forward handovers for all mobile terminals. N_{OOR} denotes the total number of OOR-RM cells caused by congestion in the MSC and in the base stations and in parenthesis the total number of OOR-RM cells caused by the used handover protocol.

For all runs between 5812 and 6189 MSC information messages are sent from the base stations to the MSC, causing an additional transfer rate of about 10 cells per second between the base stations and the MSC.

The following figures 12 to 20 are selected from the base station with the highest maximal queue length $q_{\max}$ during a certain run. The results of these experiments show that FERM and particularly its adaptation FERMA are effective and compare favorably with ERICA+ regarding the following important criteria:

Efficiency: In the figures 12, 14, 16, 18, 19 and 20 we show typical outcomes of the queue length process in the considered base station. Without any exception high peaks reflect the impact of a forward handover.

The corresponding histograms (see figures 13, 15 and 17) illustrate that FERM can control the queue length well on the desired low level and that ERICA+ and the FERM-adaptation can control the queue length well around the chosen target point q_0. For instance, for the selected fixed queueing delay t_0 without any CBR or VBR background traffic load and with a mean BER of 10^{-4} in the related radio link a base station has a target queue length q_0 of approximately 34 ABR cells.

The combination of handover signaling and ABR flow control together with an optional VS/VD-approach in the MSC has the expected positive influence on each algorithm.

The ratio Δ of the maximal and the mean queue length in a simulation run is defined by:

$$\Delta = \frac{q_{\max}}{\overline{q}} \tag{16}$$

For the three considered ABR flow-control algorithms we get

$$\begin{array}{lcrr} \Delta_{\text{ERICA+}} & \approx & 6.24 & (5.61) \\ \Delta_{\text{FERM}} & \approx & 22.51 & (18.95) \\ \Delta_{\text{FERMA}} & \approx & 5.41 & (4.58) \end{array}$$

where the results for VS/VD are stated in parenthesis.

Despite of the low mean queue length FERM cannot prevent high values at all. For the same target point q_0 and a comparable variance our FERM-adaptation is slightly superior to ERICA+.

Robustness: We are mainly interested in the stability and efficiency of our FERM-adaptation. The performed simulation runs show that the FERM-adaptation implements

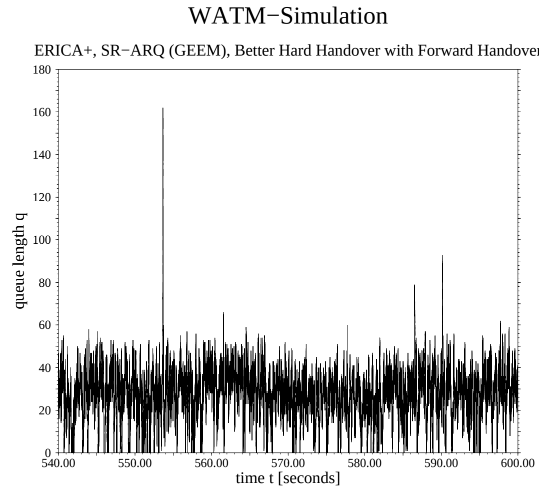

Figure 12: Queue length process of ERICA+

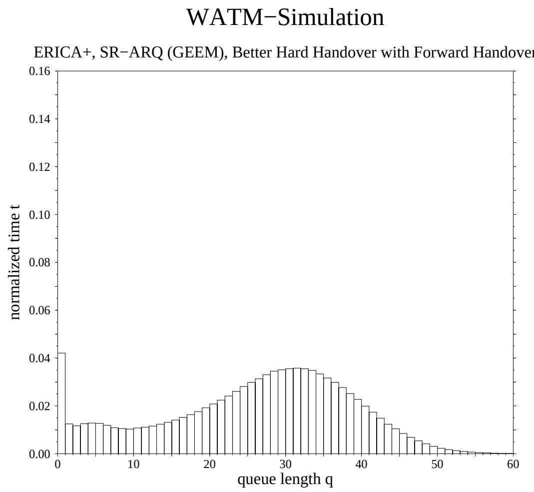

Figure 13: Queue length histogram of ERICA+

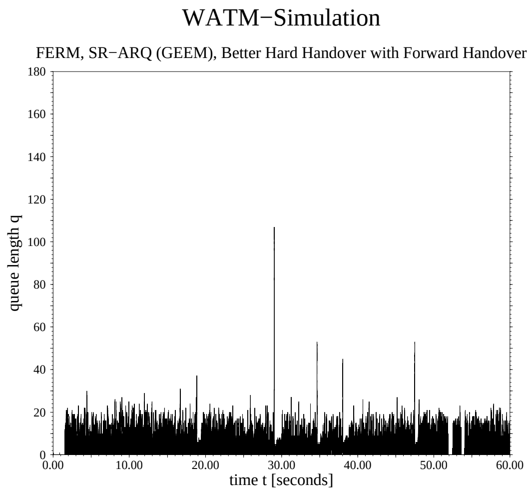

Figure 14: Queue length process of FERM

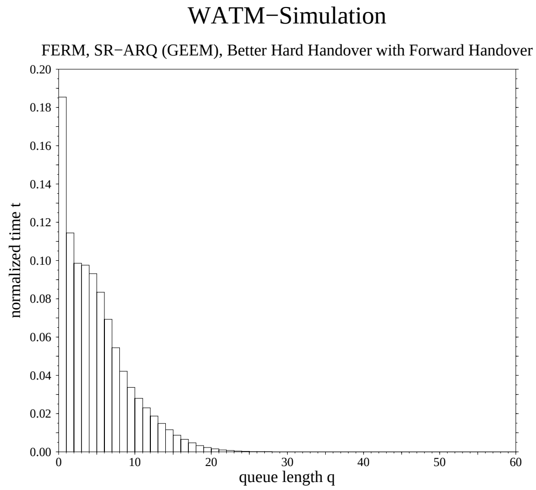

Figure 15: Queue length histogram of FERM

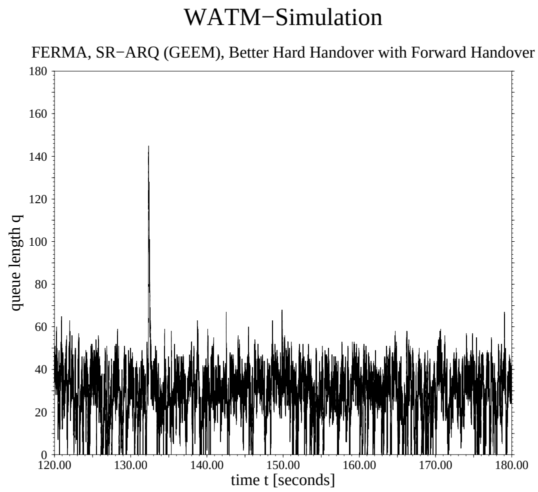

Figure 16: Queue length process of FERMA

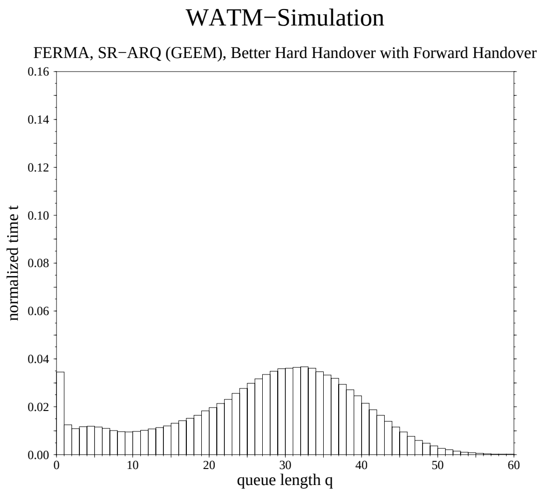

Figure 17: Queue length histogram of FERMA

a stable controller that is able to cope with the overload caused by announced backward handover events and by different error conditions in the base station transmission areas. Moreover, it can limit the queue length well around

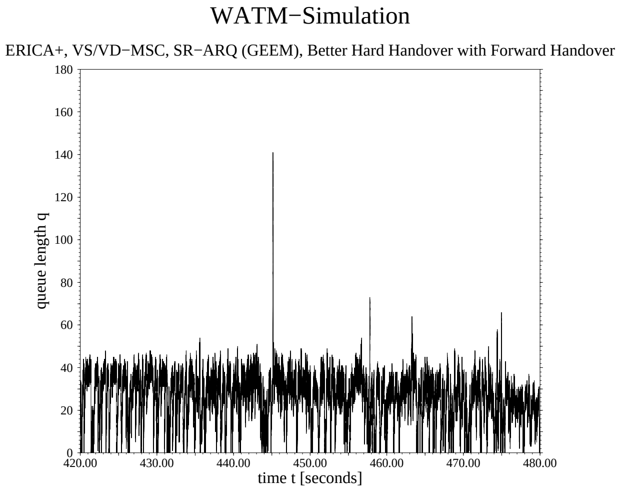

Figure 18: Queue length process of ERICA+ with VS/VD

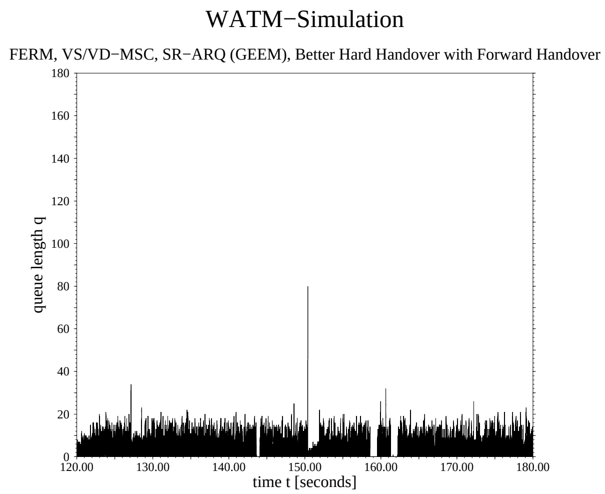

Figure 19: Queue length process of FERM with VS/VD

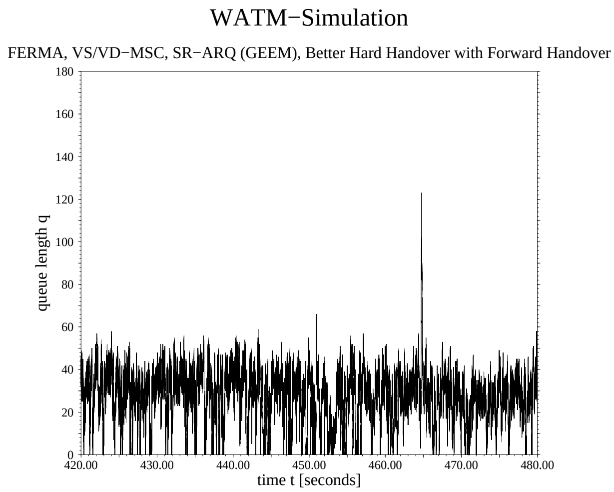

Figure 20: Queue length process of FERMA with VS/VD

the selected operation point q_0. However, forward handover events may degrade the queue length performance as it is expected from our previous experiments with ERICA and ERICA+ (cf. [13]).

Fairness: The experiments prove that FERMA guarantees each ABR connection the desired fair share of the current available ABR target cell rate. Figure 21 shows the fair bandwidth allocation of FERMA among the different ABR connections in a base station. The dashed line pictures the switch-internal ER for all ABR connections in the considered base station whereas the solid lines represent the current cell rates of the three involved ABR sources.

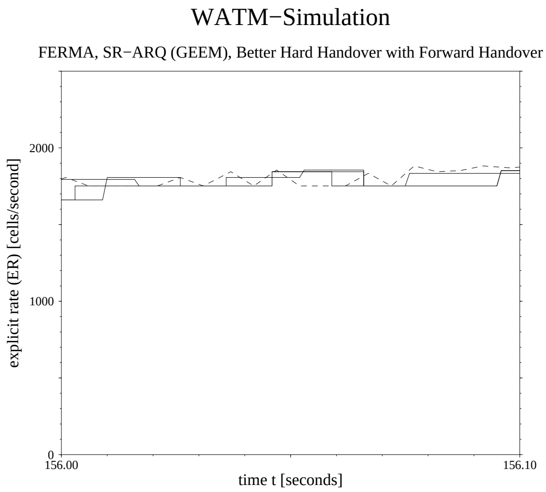

Figure 21: Fairness of FERMA (BS 1)

This fairness is achieved by using only local information.

By these results we conclude that our adaptation of FERM, even without an optional VS/VD-approach, provides a feasible, efficient, robust and fair alternative to ERICA+ for rate-based ABR flow control in a WATM network. The fuzzy controller does not require accurate information. Nevertheless, due to its fuzzy nature it can guarantee the effectiveness and robustness of the control in the highly non-stationary error and load environment of a wireless ATM network.

5 CONCLUSION

In the paper we have considered the impact of backward and forward handover events in a wireless ATM network on the rate-based ABR flow-control algorithms ERICA+, FERM and our adaptation of FERM with and without an optional VS/VD-approach in the MSC.

The simulation results show that by our improved hard handover protocol all three ABR flow-control algorithms can handle backward hard handoffs well, i.e. without a congestion in the new base station reached by moving mobile terminals. However, the observed moderate congestion caused by forward handovers of the mobile terminals cannot be avoided. Future work has to cope with this problem.

In conclusion, we think that our FERM-adaptation provides a feasible alternative approach for rate-based ABR flow control in a wireless ATM network.

APPENDIX

In the appendix we present the linguistic rules of the original FERM algorithm (R1–R11) and the changed or additional linguistic rules of our FERM-adaptation (R7b, R12–R21). Furthermore, we state the chosen parameters of the membership functions $m_{\Delta q}$ and $m_{\Delta g}$ of the linguistic variables Δq and Δg.

LINGUISTIC RULES OF FERM/FERMA

If the buffer (length) is empty,
then the flow rate should be very high. (R1)

If the buffer (length) is moderate and
the rate of change is decreasing fast, (R2)
then the flow rate should be high.

If the buffer (length) is moderate and
the rate of change is decreasing slow, (R3)
then the flow rate should be high.

If the buffer (length) is moderate and
the rate of change is zero, (R4)
then the flow rate should be medium.

If the buffer (length) is moderate and
the rate of change is increasing slow, (R5)
then the flow rate should be little.

If the buffer (length) is moderate and
the rate of change is increasing fast, (R6)
then the flow rate should be little.

If the buffer (length) is full and
the rate of change is decreasing fast, (R7)
then the flow rate should be medium.

If the buffer (length) is full and
the rate of change is decreasing slow, (R8)
then the flow rate should be little.

If the buffer (length) is full and
the rate of change is zero, (R9)
then the flow rate should be very little.

If the buffer (length) is full and
the rate of change is increasing slow, (R10)
then the flow rate should be very little.

If the buffer (length) is full and
the rate of change is increasing high, (R11)
then the flow rate should be very little.

If the buffer (length) is full and
the rate of change is decreasing fast, (R7b)
then the flow rate should be little.

If the buffer (length) is short and
the rate of change is decreasing fast, (R12)
then the flow rate should be very high.

If the buffer (length) is short and
the rate of change is decreasing slow, (R13)
then the flow rate should be high.

If the buffer (length) is short and
the rate of change is zero, (R14)
then the flow rate should be high.

If the buffer (length) is short and
the rate of change is increasing slow, (R15)
then the flow rate should be medium.

If the buffer (length) is short and
the rate of change is increasing high, (R16)
then the flow rate should be medium.

If the buffer (length) is long and
the rate of change is decreasing fast, (R17)
then the flow rate should be medium.

If the buffer (length) is long and
the rate of change is decreasing slow, (R18)
then the flow rate should be medium.

If the buffer (length) is long and
the rate of change is zero, (R19)
then the flow rate should be little.

If the buffer (length) is long and
the rate of change is increasing slow, (R20)
then the flow rate should be little.

If the buffer (length) is long and
the rate of change is increasing high, (R21)
then the flow rate should be very little.

PARAMETERS OF FERMA

Each row k of the following tables 3, 4 shows the angle points $(x_{k,1};y_{k,1}),\ldots,(x_{k,4};y_{k,4})$ of the membership function m_{v_k} of the linguistic value v_k, $1 \leq k \leq n_v$.

Table 3: Parameters of the linguistic variable $\Delta q = q/q_0$ (see figure 5)

k	$m_{\Delta q_k}$
1	$(\ 0.00;1),(\ 0.00;1),(\ 0.20;1),(\ 0.40;1)$
2	$(\ 0.30;0),(\ 0.50;1),(\ 0.80;1),(\ 0.90;0)$
3	$(\ 0.80;0),(\ 0.90;1),(\ 1.10;1),(\ 1.20;0)$
4	$(\ 1.10;0),(\ 1.20;1),(\ 1.40;1),(\ 1.60;0)$
5	$(\ 1.50;0),(\ 1.70;1),(\ 2.00;1),(\ 2.00;1)$

Table 4: Parameters of the linguistic variable $\Delta g = g/N$ (see figure 6)

k	$m_{\Delta g_k}$
1	$(-1.00;1),(-1.00;1),(-0.20;1),(-0.15;0)$
2	$(-0.20;0),(-0.15;1),(-0.10;1),(-0.05;0)$
3	$(-0.10;0),(-0.05;1),(\ 0.05;1),(\ 0.10;0)$
4	$(\ 0.05;0),(\ 0.10;1),(\ 0.15;1),(\ 0.20;0)$
5	$(\ 0.15;0),(\ 0.20;1),(\ 1.00;1),(\ 1.00;1)$

Notice:

- If $(x_{k,1};y_{k,1})$ is equal to $(x_{k,2};y_{k,2})$, then $m_{v_k}(x) = y_{k,1}$ for all $x \leq x_{k,1}$.
- If $(x_{k,3};y_{k,3})$ is equal to $(x_{k,4};y_{k,4})$, then $m_{v_k}(x) = y_{k,4}$ for all $x \geq x_{k,4}$.

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