

# AQUILA network architecture: first trial experiments

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**Abstract** — The paper presents trial experiments with IP QoS network services (NS) defined and implemented in the AQUILA pilot installation. The AQUILA NSs (premium CBR, premium VBR, premium multimedia and premium mission critical) provide a framework for supporting a variety of applications generating both streaming and elastic traffic. The measurement experiments confirm that AQUILA architecture differentiates the QoS offered to these NSs. The presented numerical results were obtained in the test network installed in the Polish Telecom (Warsaw) consisting of 8 CISCO routers.

**Keywords** — IP QoS, measurements.

## 1. Introduction

The IP QoS networks have gained recently a significant attention. The future Internet architecture will have to offer QoS as well as keep its current advantages of scalability and simplicity. The differentiated service (DiffServ) architecture [1, 2] is considered to be a promising solution for IP QoS networks. The DiffServ architecture is not a complete solution rather it is a framework that defines basic mechanisms and rules for providing QoS. The AQUILA project aims at developing complete QoS architecture for IP networks that enhances the original DiffServ concept. The main innovations of AQUILA include the definition of network services, specification of admission control rules and specification of signalling mechanisms for dynamic resource reservation. The AQUILA project adds new element to the DiffServ enabled network by implementation of resource control layer (RCL) that can be treated as a distributed bandwidth broker. The RCL implements all logic necessary for providing end-to-end dynamic QoS guarantees to the end-users.

The AQUILA project is on going activity. Currently the first phase of RCL development was finished, that resulted in the implementation of the AQUILA prototype in 3 different test-beds. The main AQUILA test-bed is located in Polish Telecom in Warsaw. The paper presents comprehensive description of basic AQUILA functions and additionally presents some results of the first trial experiments carried out in the Warsaw test-bed.

The paper is organized as follows. In Chapter 2 the basic concepts of AQUILA network are briefly described. The Chapter 3 introduces reader to the AQUILA test-bed used in the trial experiments. The trial results are presented in Chapter 4. Finally, the Chapter 5 concludes and summarizes the paper.

## 2. AQUILA network and service architecture

The AQUILA network architecture distinguishes two types of network elements (similarly as in DiffServ): the edge devices (ED) and core routers (CR). The EDs connect end users to the network and implement all per flow oriented traffic control functions e.g. traffic policing, marking etc. The CRs perform only packet forwarding according to the assigned per hop behaviour (PHB). The CRs do not distinguish individual flows rather they operate on behaviour aggregates (the collections of packet that belongs to the same traffic class).

In AQUILA architecture (Fig. 1), additional layer, named resource control layer (RCL), was added on the top of DiffServ enabled network.

This layer is responsible for controlling and managing network resources (the RCL represents the control plane while the DiffServ network represents data plane of the AQUILA network). The RCL is subdivided into two sublayers implemented by software-based components i.e. resource control agent (RCA) and admission control agents (ACA). The ACA agent is responsible for performing admission control, while the RCA manages the resource provisioning and distribution (or redistribution) between ACA agents.

For providing QoS differentiation to users traffic a set of four NSs was defined and implemented. The particular NSs differ with respect to QoS objectives, traffic characterization and supported traffic type (streaming or elastic). Each NS is designed for effective transmission of traffic produced by applications with similar QoS requirements (e.g. voice, video or data applications). The NSs are mapped into a set of traffic classes (TCL) that define appropriate traffic handling rules for meeting NS objectives, i.e. traffic conditioning mechanisms, admission control algorithms and PHB rules.

### 2.1. AQUILA network services

The following QoS NSs were defined in AQUILA: premium CBR (PCBR), premium VBR (PVBR), premium multimedia (PMM) and premium mission critical (PMC) in addition to standard best effort Internet service. The first two services are for streaming traffic while the other are for elastic traffic.

The PCBR is intended for applications that require constant bit rate (CBR traffic) with very low packet transfer delay and packet losses e.g. voice applications. The user

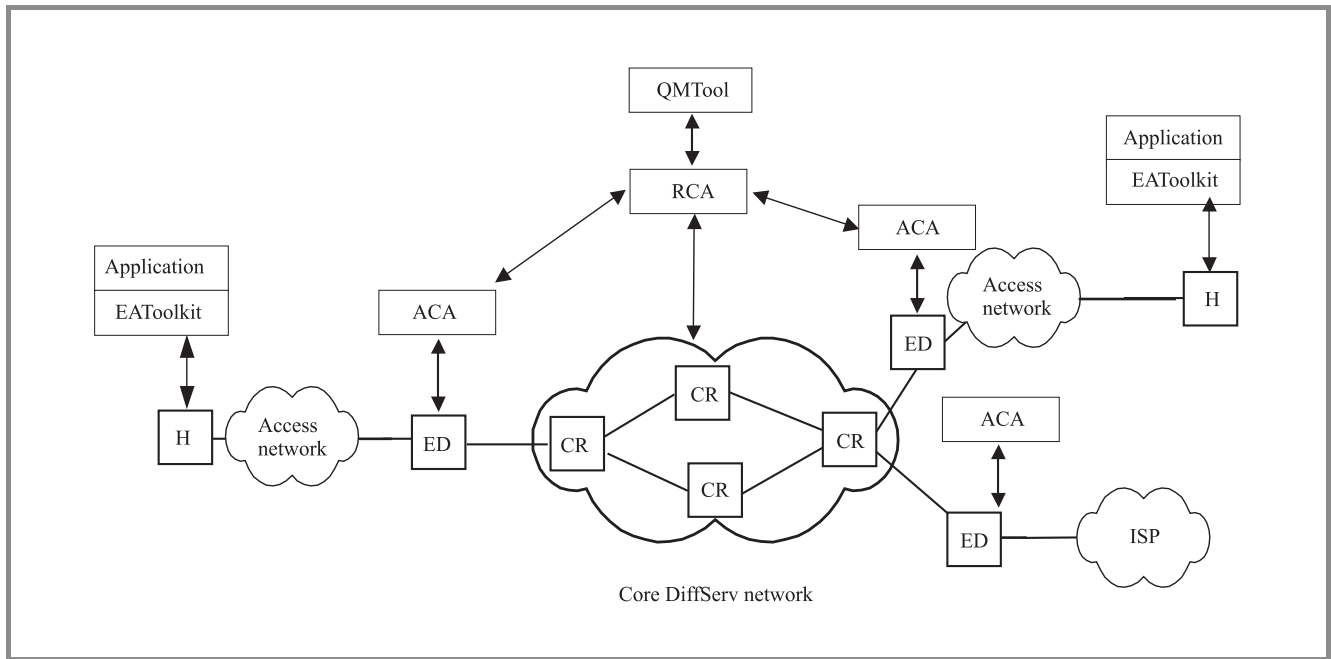


Fig. 1. General AQUILA network architecture.

traffic in this case is characterized by peak bit rate, only. The next NS (PVBR) is designed for applications requiring variable bit rate (VBR traffic). This service provides similar QoS guarantees as PCBR. Typical application of this NS is video transmission. The user traffic is characterized by sustainable and peak bit rates.

The remaining NSs are intended for elastic traffic i.e. TCP-controlled. The PMM service uses single rate characterization (sustainable bit rate). This service allows for much higher burst tolerances comparing to PCBR. Therefore, the PMM service can be seen as a special case of VBR service with the peak bit rate equal to the link bit rate. This service is mainly intended for long life greedy TCP connections. On the contrary, the PMC service is designed for short life non-greedy TCP connections. In this service, the user traffic is characterized, similarly as in case of PVBR service, by the peak and sustainable bit rates.

2.2. AQUILA traffic handling mechanisms

The AQUILA NSs are mapped to appropriate traffic classes TCL (currently one NS is mapped to one traffic class). Depending on the TCL, the traffic conditioning (policing) is performed by single or dual token bucket algorithm. The TCL1 class (employed by PCBR service) uses single token bucket algorithm (peak bit rate) while the TCL2 (used by PVBR service) uses dual token algorithm (peak and sustained bit rates). In both cases the excess traffic is dropped (only conforming packets are allowed to enter the network). In the case of TCL3 traffic class (used by PMM) the user traffic is characterized by single token bucket algorithm while in TCL4 (used by PMC) by dual token bucket. In both cases the excess traffic is marked as “out of the profile” and entered to the network.

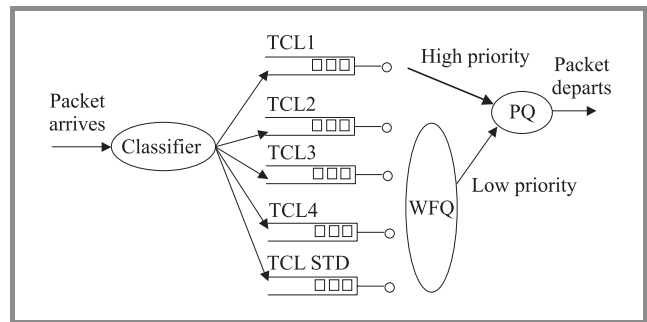


Fig. 2. Routers output port architecture.

After passing conditioning block, the packets are buffered in separate queues according to the traffic class they belong (the conditioning is done only in the ED). The TCL1 and TCL2 queues use simple drop tail queue management mechanism while TCL3 and TCL2, since they are designed for elastic traffic, employ the WRED (weighted random early discard) algorithm to tailor the access of “in profile” and “out of profile” packets to the output link. The TCL1 queue has non-preemptive priority over the other queues in the access to the output link (priority queuing scheduler – PQ). The remaining four queues (including the queue for best effort traffic) are served by WFQ (weighted fair queuing) scheduler. The AQUILA scheduling algorithm is an equivalent of CBWFQ (class based WFQ) scheduler available on CISCO routers (Fig. 2).

2.3. Resource management

The resource distribution is done on the per traffic class basis, i.e. resources assigned to a particular class cannot be used by other classes (there is no dynamic resource

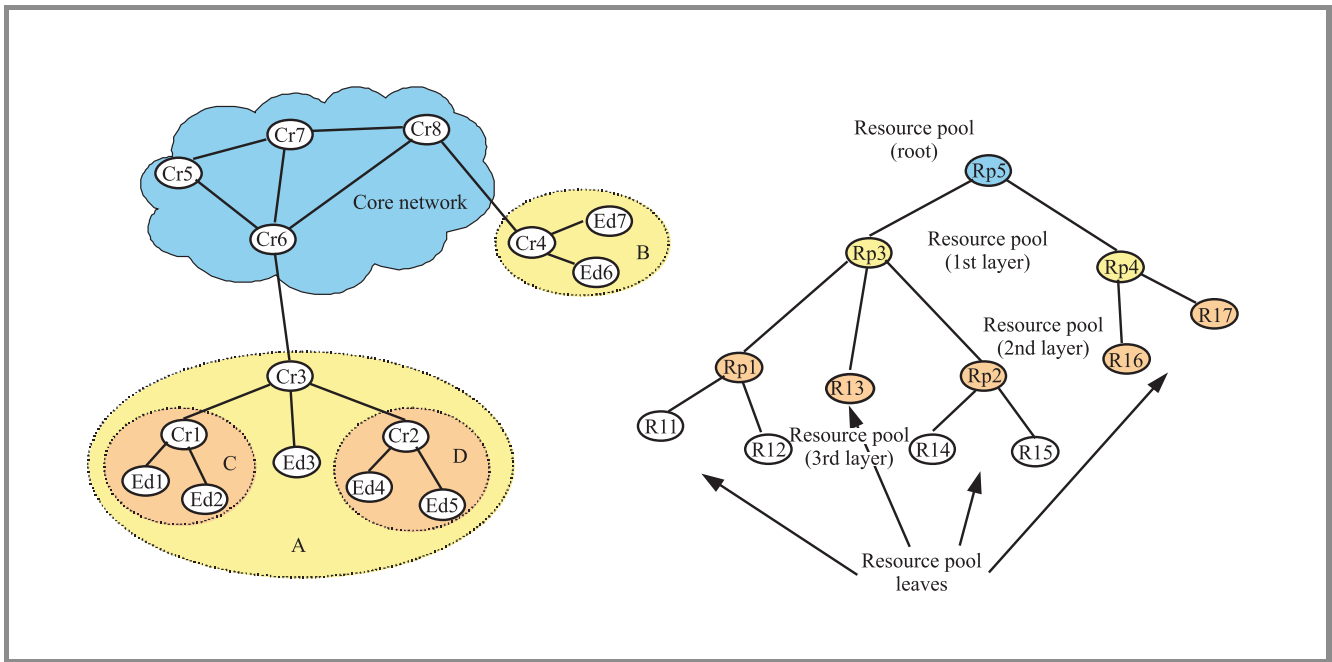


Fig. 3. Resource pools.

sharing between AQUILA traffic classes). As a result the network is divided into 5 layers each representing virtual networks related to particular traffic class. Each ACA agent represents one ED. The ACA agent accepts request for resources up to a given limit. To calculate the admission limits the RCL takes into account the prediction of traffic between EDs, network routing, etc. The resources assigned to a given ED represent total traffic that can be accepted by its ACA agent irrespectively of the traffic destination (the resources are assigned on per ACA basis).

Usually precise prediction of traffic demands in the Internet is almost impossible. Therefore, additional adaptive resource management mechanism was developed in AQUILA, which aims to improve overall network resource utilization. This mechanism allows shifting resources between ACA agents if the resource utilization at certain point in the network is lower than assumed threshold. To facilitate this, resources assigned to ACA agents are grouped into, so called, resource pools. The resource pool represents a part of network resources that can be shared by its ACA agents. The resource pool can be further aggregate creating higher level of resource pools and so on. Any level of resource pool hierarchy can be defined depending on network topology. The topology structure where resource pools can be easily defined is the tree topology. In the simplest scenario, one resource pool can be created for each tree node (the network nodes on the lowest level represents ACA agents, and are called resource pool leaves). This approach can be generalized for tree like structures of network sub-areas.

The exemplary resource pool hierarchy is shown in Fig. 3. The root of the resource pool hierarchy represents overall network resources. In the exemplary network from Fig. 3 we have two network sub-areas (A and B) for which the re-

source pool Rp3 and Rp4 are created. The resource pools Rp3 and Rp4 form the first level of the resource pool hierarchy. The Rp3 and Rp4 are further shared by the resource pools of the second hierarchy level. This process is continued until the lowest level of resource pool hierarchy is reached. The lowest resource pool in each tree branch represents the resource pool leaf, which is associated with ACA.

2.4. Admission control

Typical IP network offers only the best effort service. Because this service does not provide any QoS guarantees no admission control is necessary. Consequently, there is no control over the number of flows that are handled by the network. In AQUILA project new QoS services were defined with differentiated QoS requirements. Therefore, the admission control methods, capable to provide required QoS guarantees, had to be defined. In AQUILA the QoS guarantees are provided to the flow, which is defined as an unidirectional flow of IP packets that can be distinguished at the network entry based on the contents of packets headers (source, destination IP addresses, protocol type etc.). This definition is essentially compliant with the concept of the flow used in DiffServ architecture. Generally, two types of admission control algorithms can be distinguished i.e. the methods based on the declaration submitted by the user and methods that additionally take into account some traffic measurement (apart the declarations). The first approach was taken by AQUILA project. A request for network resources is accepted or rejected based on the traffic descriptors provided by the user (special signalling procedure was developed for this purpose). The objective of the AQUILA project was to ver-

ify if similar approach (declaration based admission control) as used in ATM network could also be applied to IP networks.

In the AQUILA architecture the admission decision is performed only at the network ingress and egress. This makes the admission control algorithm more difficult (or uncertain) as link-by-link verification of resource availability is not possible. To perform the admission control at the ingress the single link model was assumed. It means that, for each traffic class, the admission control algorithm operates as if there was only one link with capacity ( $C$ ) and buffer size ( $B$ ) in the network. The parameter ( $C$ ) corresponds to the amount of network resources assigned to the particular ACA agent where as the parameter ( $B$ ) is related to the buffering capacity provided by the network (currently it is set to the smallest buffer size among all routers devoted to the particular traffic class). Whenever below parameters ( $C$ ) or ( $B$ ) are mentioned they correspond to the capacity or buffer space dedicated to serve the given traffic class.

#### 2.4.1. Admission control algorithm for streaming traffic characterized by single token bucket

The TCL1 class uses peak bit rate allocation scheme [4]. Within this class the flows are characterized by parameters of single token bucket algorithm (this parameter correspond to the peak bit rate (PBR) and peak bit rate tolerance (PBRT). In the AQUILA architecture, the TCL1 traffic is served with the highest priority. It means that the TCL1 traffic is not mixed with other traffic in the network. Small variation in the TCL1 traffic rate can be still present due to the  $PBRT$  parameters and influence of residual packet transmission time of low priority traffic. Taking this into account, it can be assumed that the TCL1 streams have negligible packet delay variation [11]. Consequently, the worst-case traffic pattern for the superposition of a number of TCL1 flows takes the form of poissonian stream (with the mean rate equal to the sum of the  $PBR$  parameters of the particular flows).

New flow characterized by  $PBR$  and  $PBRT$  parameters, is admitted if the following condition is satisfied:

$$PBR + \sum_i PBR_i \leq \rho C. \quad (1)$$

Parameter  $\rho$  ( $\rho < 1$ ) specifies the admissible load of capacity allocated to the TCL1 class. The value of  $\rho$  can be calculated from the analysis of M/D/1/B system taking into account the target packet loss ratio and the buffer size [5].

#### 2.4.2. Admission control algorithm for streaming traffic characterized by dual token bucket

In the case of TCL2 traffic class rate envelope multiplexing (REM) scheme is assumed for guaranteeing low packet

delay [4]. Therefore, the only QoS parameter that requires concern is the packet loss rate. In the REM multiplexing the buffer has to be dimensioned for absorbing, so called, packet scale congestion (simultaneous arrival of packets from different sources). For this purpose the N\*D/D/1 queuing system analysis can be used.

In the TCL2 class, each flow is characterized by parameters of dual token bucket algorithm: the  $PBR$  together with the  $PBRT$  and the sustainable bit rate ( $SBR$ ) together with the burst size ( $BSS$ ). It is commonly assumed that the worst-case traffic pattern for given values of  $PBR$ ,  $SBR$  and  $BSS$  is of the ON/OFF type.

The proposed admission method for TCL2 is based on the notion of effective bandwidth. One may find a number of methods for calculating effective bandwidth [4]. For its simplicity the methods proposed in [12] was chosen for AQUILA. In this method the value of effective bandwidth,  $Eff(.)$ , is calculated on the bases of  $PBR$ ,  $SBR$  and  $BSS$  parameters taking into account the target packet loss rate. The new flow with  $Eff(.)$  is admitted if the following condition is satisfied:

$$Eff(.) + \sum_i Eff(i) \leq C. \quad (2)$$

The effective bandwidth usually depends on the link capacity. In the case of AQUILA admission concept (admission performed only at the ingress) this requires to use some reference link capacity (not the admission limit  $C$ ). In AQUILA the rate of the first link connecting the ED to the CR is used.

#### 2.4.3. Admission control algorithm for elastic traffic characterized by single token bucket

In the case of TCL3, each flow is characterized by parameters of single token bucket algorithm that correspond to the  $SBR$  and the  $BSS$ . Usually, the  $BSS$  values are rather large what allows high variability of submitted traffic. Comparing to TCL2 or TCL4, the declaration of the  $PBR$  parameter is omitted. In fact, the  $PBR$  is only limited by the link bit rates.

Taking into account that the traffic flows submitted to TCL3 class are TCP-controlled, only rough QoS guarantees are assumed to be provided. Therefore, an admission control method that maximizes the network utilization can be employed in this case. The new flow characterized by  $SBR$ ,  $BSS$  and  $MTU$  (maximum transfer unit) is admitted only if the following conditions are satisfied:

$$SBR + \sum_i SBR_i \leq C, \quad (3)$$

$$MTU + \sum_i MTU_i < B. \quad (4)$$

Remark, that depending on the value of the buffer size ( $B$ ) the multiplexing in this class can follow the REM

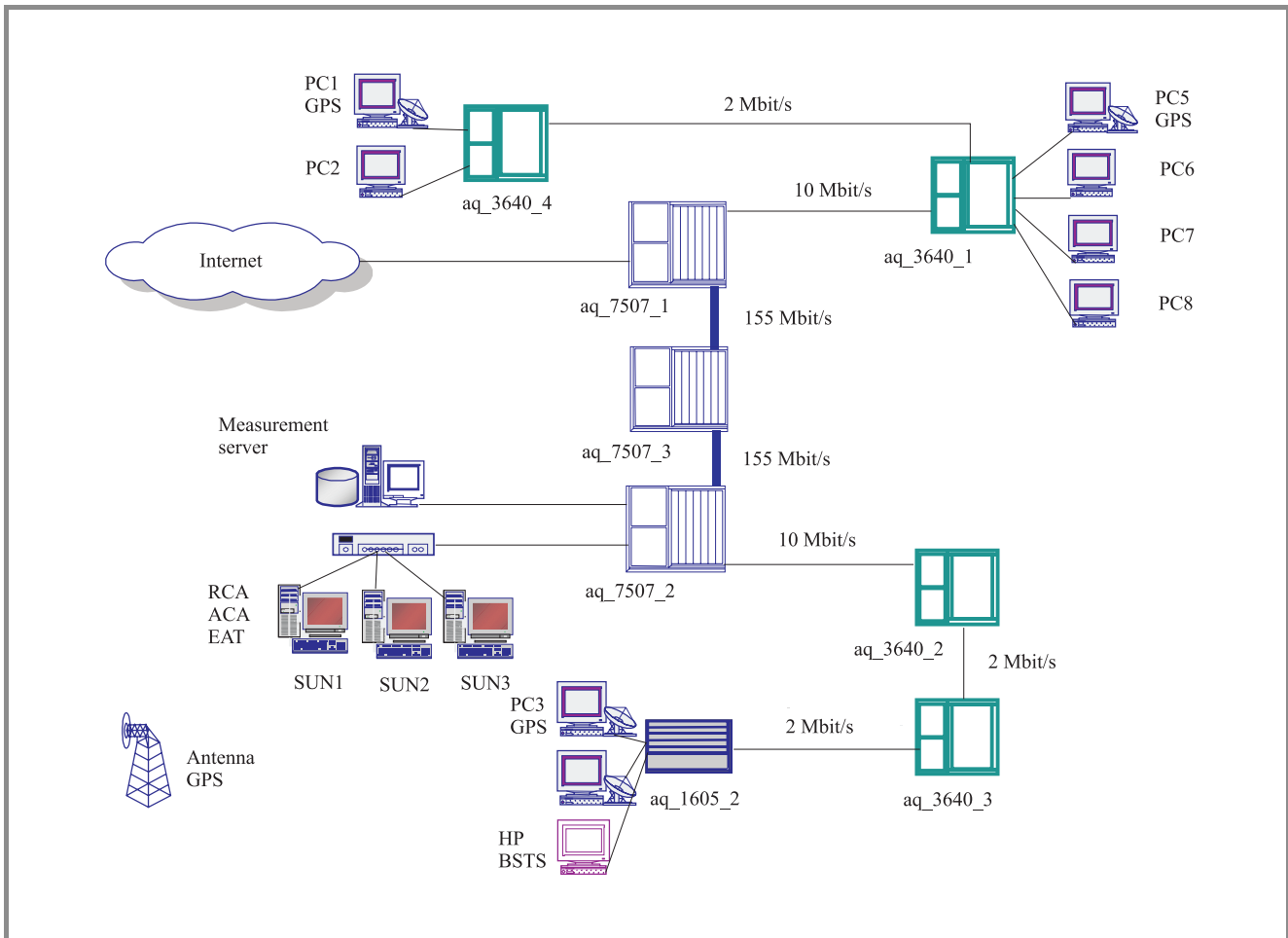


Fig. 4. AQUILA test-bed configuration: PC1-8 – terminals, SUN1-3 – sun workstations with implemented RCA, ACA and EAT modules, aq\_1605, aq\_3640, aq\_7507 – CISCO routers.

or the rate sharing multiplexing (RSM) scheme [4]. The RSM multiplexing corresponds to the case of large buffers capable to absorb temporary traffic fluctuations (to absorb packet burst scale congestion). In this case, the second condition (related to buffer) can be omitted.

#### 2.4.4. Admission control algorithm for elastic traffic characterized by dual token bucket

In the TCL4, a flow is characterized by parameters of dual token bucket algorithm, similarly as in the case of TCL2 class. Because this class does not guarantee any delay parameters the RSM multiplexing scheme was assumed. The proposed admission control algorithm provides the service rate that will guarantee no losses for packets that are within traffic contract. New flow characterized by  $PBR$ ,  $SBR$  and  $BSS$  is accepted if the following condition is satisfied:

$$Eff(.) + \sum_i Eff(i) \leq C. \quad (5)$$

The effective bandwidth in this case is calculated as follows [13]:

$$Eff(.) = \max \left\{ SBR, \frac{PBR \cdot T}{B/C + T} \right\}, \quad (6)$$

where,  $T = \frac{BSS}{PBR - SBR}$ .

### 3. Description of the AQUILA test-bed

The experiments were carried out in the AQUILA test-bed (Fig. 4), installed in the Polish Telecom in Warsaw. The test-bed network consisted of 8 CISCO routers (of different types) connected in the form of the chain to emulate large number of hops. The end terminals were connected to the edge routers by Ethernet ports. The access links between the ED and the first CR had capacity of 2 Mbit/s. The core routers were connected by higher capacity links (10 and 155 Mbit/s). The following types of routers were installed in the test-bed: two edge routers – 1605 (aq1605.2) and 3640 (aq3640.4), 6 core routers – 3640 (aq3640.1, aq3640.2, aq3640.3) and 7507 (aq7507.1, aq7507.2, aq7507.3). The core and edge routers were configured according to the



AQUILA architecture design. The AQUILA software was installed on 3 workstations. Each workstation was used for different type of RCL components (ACA, RCA, EAT).

## 4. Measurement results

### 4.1. Separation of streaming and elastic flows

The first set of experiments shows the rationale for defining separate NSs for traffic generated by streaming and elastic applications. The test traffic was generated between the end-stations PC4 and PC2 (Fig. 4) as the 200 kbit/s constant bit rate stream controlled by UDP transport protocol. Additionally, a number of greedy TCP connections was established between the end-stations PC3 and PC1. Notice that the 2 Mbit/s link connecting ED router to the core is the bottleneck link in the considered topology.

Two test cases were taken into account. First, the FIFO scheduling discipline was set-up in the ED. As a consequence, traffic produced by UDP and TCP connections was handled inside ED in the same way. In the second case, the PQ scheduler was selected in ED and UDP traffic was served in isolation from TCP traffic. The highest priority was assigned for UDP traffic because of its QoS requirements. Note that it is not reasonable to assign the highest priority for greedy TCP traffic since it can lead to bandwidth starvation for the lower priority traffic. In both tested scenarios, the performances of transferring the UDP traffic were checked by measuring the one-way packet delay and packet loss ratio QoS parameters.

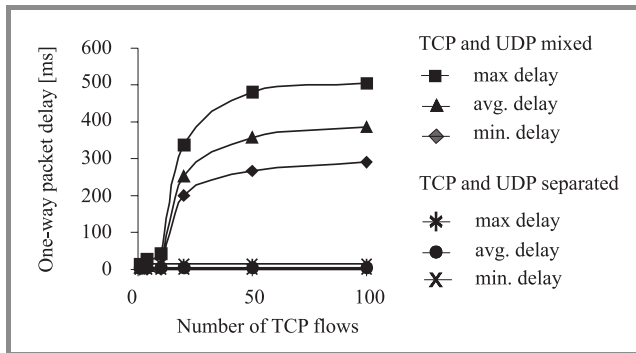


Fig. 5. One-way delay of UDP packets mixed with TCP traffic and separated from TCP traffic.

The obtained results are shown in Figs. 5 and 6. One can observe, that when TCP and UDP traffic is mixed together, the one-way delay and packet loss ratio of the UDP packets strongly depend on the number of active TCP connections competing for the bottleneck link capacity. This is the case now observed in IP networks, where the number of TCP connections is not limited by any admission control mechanism. When 100 TCP connections were set up in the network, the aggressive TCP congestion control scheme caused that the buffer in ED associated with the bottleneck link was heavily overloaded. Therefore, the delays experienced by tested UDP packets was about 500 ms.

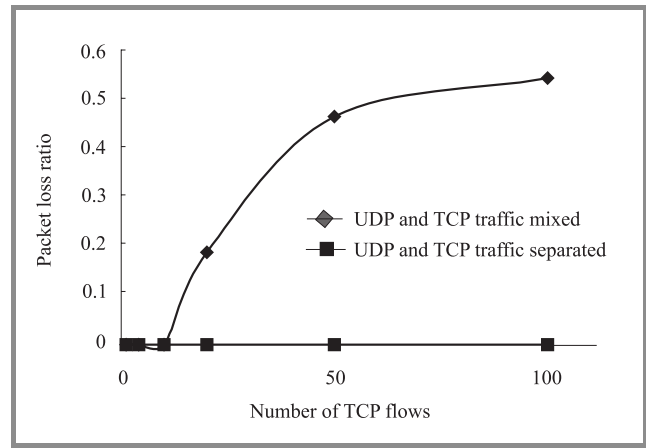


Fig. 6. Packet loss ratio of UDP packets mixed with TCP traffic and separated from TCP traffic.

The observed values of packet loss ratio were also considerably high (up to 50%).

This non desirable effect can be eliminated when UDP packets are served in the network in isolation, with highest assigned priority. In this case, no packet losses were observed and the maximum packet delay was close to 12 ms, regardless the number of active TCP connections. This result confirms that streaming and elastic traffic should be separated in the network, otherwise the QoS guarantees for streaming traffic are hard to satisfy. In AQUILA, this requirement is met by appropriate definitions of PCBR and PVBR services for streaming traffic and PMM and PMC services for elastic traffic.

### 4.2. Premium CBR service

The carried out experiments corresponding to PCBR service were aimed for measuring effectiveness of CBR flows transmission. For the test scenario was assumed that the QoS parameters of carrying traffic were measured under the maximum submitted traffic allowed by the admission control of the TCL1 class. The test traffic was modelled by a Poisson stream with constant packet lengths. Notice that such traffic represents the worst case of the superposition of large number of CBR streams. To take into account the impact of other classes on the TCL1 packets (residual transmission time of low priority packets) the background traffic was also added to the STD class. The background traffic filled the rest of link capacity not dedicated to TCL1.

In the following experiments, 200 kbit/s of the access link capacity was reserved for TCL1. Furthermore, the TCL1 queues in the routers were set to 5 packets to guarantee low packet delay. The performance of TCL1 was validated assuming target packet loss ratio (Ploss) equal  $10^{-2}$ . According to the specified admission control algorithm, the maximum admissible load in this case (acc. to the M/D/1 system analysis [4]) is  $r = 0.685$ , what is equivalent to 137 kbit/s.

The foreground traffic was transmitted between PC1 and PC3 terminals (Fig. 4) while the background traffic was generated only to the access link. The background traffic was created as a mix of packets with different lengths: 7% with 44 bytes, 21% with 256 bytes and 72% with 1280 bytes. Both foreground and background traffic was transmitted using UDP protocol.

The characteristic of packet loss rate as a function of the TCL1 traffic volume is presented in Fig. 7.

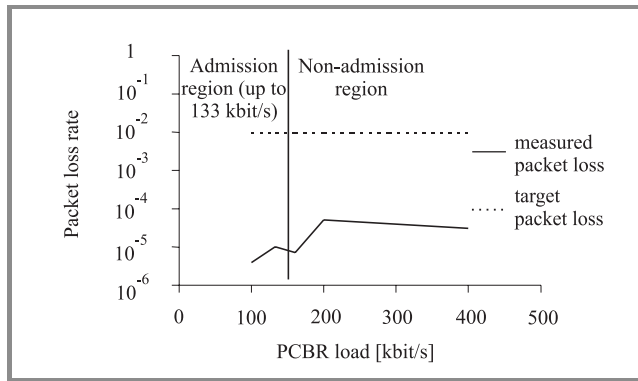


Fig. 7. Packet loss rate versus TCL1 traffic load.

One can observe that the measured value of packet loss rate are in the range of  $10^{-5}$  and they are significantly below the assumed target value  $10^{-2}$  even for the load above the admission region (133 kbit/s). This is rather expected result since the TCL1 traffic is served with higher priority with the effective service rate of 2 Mbit/s (instead of 200 kbit/s as was assumed for the admission control algorithm). Anyway, increasing TCL1 traffic significantly above the assumed limit (133 kbit/s) can degrade the quality experienced by packets carried in low priority classes (e.g. TCL2). The recommended admissible load of TCL1 traffic is approximately 10% of total link capacity.

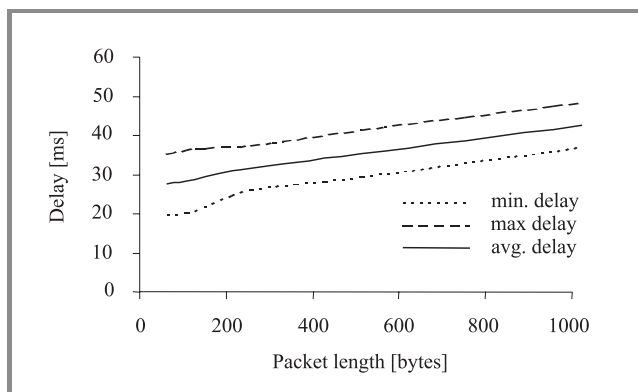


Fig. 8. One-way delay versus TCL1 packet length.

The characteristics of one-way packet delay as a function of TCL1 packet length are depicted in Fig. 8. These curves were measured assuming that Poisson traffic with the rate equal to 133 kbit/s (up to admission limit) was submitted to TCL1. The background traffic of ON/OFF type was

submitted independently to each intermediate link (Fig. 4), with the peak bit rate equal to the appropriate link rate. The maximum observed delay was below 50 ms. This value is acceptable for most voice applications, that tolerate delay in the order of 150 ms (with codec and packetization delay).

### 4.3. Premium VBR service

The PVBR service was designed for real time applications producing variable bit rate traffic. The QoS objectives for this service are low packet transfer delay ( $\leq 150$  ms) and low packet loss ratio ( $\leq 10^{-4}$ ). In the followed experiments, the target packet loss ratio was fixed to  $10^{-2}$ . The presented measurement experiments correspond to validation of packet loss ratio as well as end-to-end delay measured for artificial flows. Traffic served by TCL2 was generated between PC3 and PC1 while traffic served by TCL1, TCL3, TCL4, and TCL5 was generated between HP BSTS and aq\_3640\_3 router. The bandwidth dedicated for TCL2 class (on 2 Mbit/s access link) was 300 kbit/s. The following bandwidths were allocated to the other traffic class: TCL1: 200 kbit/s, TCL3: 600 kbit/s, TCL4: 100 kbit/s, and TCL5: 800 kbit/s. Output buffer in ED dedicated for TCL2 was assumed to be 5 packets long. The aggregated traffic of TCL2 class was assumed to be superposition of ON/OFF sources and was modelled by Markov modulated deterministic process (foreground traffic). Flows of constant bit rate sufficient to load the network resources dedicated to the other traffic classes were used as background traffic flows.

In the first experiment the packet loss ratio and the end-to-end packet delay were obtained as a function of the number of admitted flows (Fig. 9). In this case each ON/OFF flow was described by the following parameters:  $PBR = 32$  kbit/s,  $SBR = 16$  kbit/s,  $BSS = 15000$  bytes, packet size = 500 bytes. Effective bandwidth for each flow was equal to 27.29 kbit/s. Number of admitted flows, according to the AC algorithm, was 10. Values of traffic descriptors used in the following experiments correspond to the traffic generated by a voice applications.

Table 1  
The measured values of QoS parameters

Min. delay [ms]	Max delay [ms]	Avg. delay [ms]	Packet loss ratio
15	44	26	$10^{-5}$

The second experiment was done for the superposition of 30 ON/OFF flows served by TCL2 (to achieve greater multiplexing gain). Each ON/OFF flow was characterized by:  $PBR = 18.5$  kbit/s,  $SBR = 5.6$  kbit/s,  $BSS = 526$  bytes, and packet size = 256 bytes. Effective bandwidth of each flow was 9.97 kbit/s. The sum of the peak bit rates of 30 flows was 555 kbit/s while the sum of the effective bandwidths over all flows was 299.1 kbit/s. The obtained results are presented in the table below. The measured values of QoS parameters satisfy requirements and

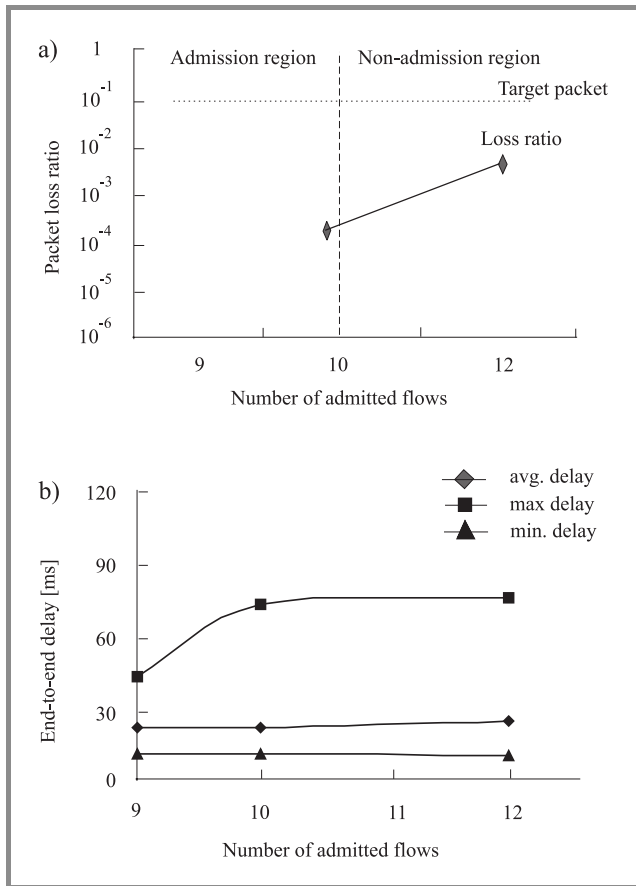


Fig. 9. Packet loss ratio (a) and end-to-end (b) delay versus number of admitted flows.

objective of TCL2 (Table 1). The values of packet loss ratio ( $10^{-5} - 10^{-3}$ ) are smaller than the assumed target value ( $10^{-2}$ ).

Some trials were also carried out with real video application (e.g. NetMeeting). Unfortunately, it appeared that it is very difficult to tune traffic descriptors for real application, like NetMeeting. This suggest that traffic declarations should be limited to the peak rate while admission control should get additional information about carried traffic from measurements.

#### 4.4. Premium multimedia

The PMM service was mainly designed for effective support of greedy TCP-controlled flows. The objective of this service is to guarantee a minimum throughput to the TCP flows. The measurement results presented below were obtained assuming that the traffic generated by a number of TCP greedy sources (between PC1 and PC3) was submitted to the TCL3 class while the CBR background traffic was submitted to other NSs with the maximum possible rates (according to the assigned capacity for given service). In this way the capacity available for the TCP connections was limited to the capacity allocated to TCL3 class. In the considered case this capacity was equal to 600 kbit/s with target utilization factor set to 0.9 (this parameter rep-

resents target utilization for “in-profile” packets) what gives 540 kbit/s of available capacity for setting up flows. Notice that the “out-of-profile” packets in case of TCL3 (and also TCL4) are not dropped. Consequently, the considered greedy TCP flows can achieve higher rate than requested by the *SBR* parameters.

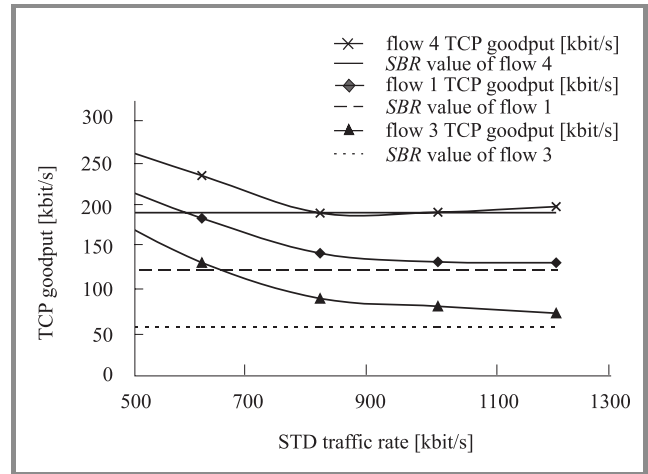


Fig. 10. TCP goodput in PMM service versus STD traffic rate.

The goodput characteristics of 4 TCP flows, with different declared *SBR* values, as a function of best effort traffic volume are depicted in Fig. 10. The assigned *SBR* values were as follows: 135, 135, 70 and 200 kbit/s. One can observe that the available capacity for PMM service is effectively used by the considered TCP connections. When the background traffic exceeds a certain threshold (in this case 800 kbit/s) the available capacity for TCL3 is limited to assumed AC limit (600 kbit/s). This capacity is shared by TCP flows roughly in proportion to their declared *SBR* rates. For example, the connections with *SBR* = 200 gets 206 kbit/s while the connection with *SBR* = 70 gets only 85 kbit/s.

Figure 11 shows the proportion of packets, marked as “in-profile” and “out-of-profile”, contributing to the throughput of 2 exemplary TCP connections. The traffic submitted into the network in excess of the traffic profile requested in the reservation is marked as “out-of-profile”. In the underload network conditions, the “out-of-profile” traffic obtains the capacity unused by the other NSs, but in time of network congestion, throughput of the TCP flow in PMM service is guaranteed roughly up to the requested *SBR* value.

By applying the WRED mechanism, one can expect that the “in-profile” packet will obtain better service, than “out of profile” packets. In AQUILA, WRED mechanism controls the access of “in-profile” and “out-of-profile” packets to the TCL3 buffer. When the average queue size exceeds a predefined threshold, incoming packets can be dropped with a certain probability. By setting different threshold values for “in” and “out” packets, one can differentiate the loss ratio of packets marked as “in” and “out of profile”. Figure 12 shows the received packet loss characteristic for “in” and “out” packets as a function of the number of TCP



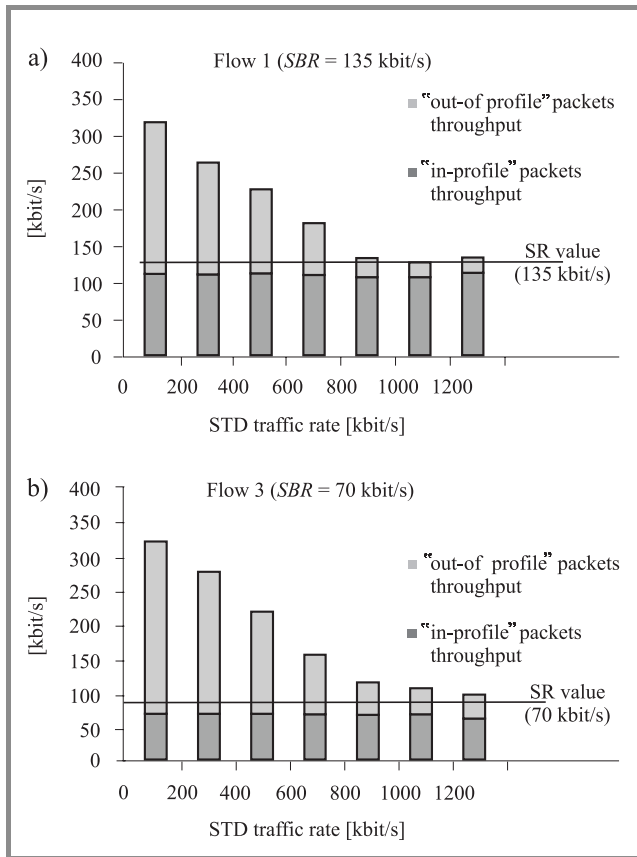


Fig. 11. Throughput of “in-profile” and “out-of-profile” packet streams within flow 1 (a) and flow 3 (b).

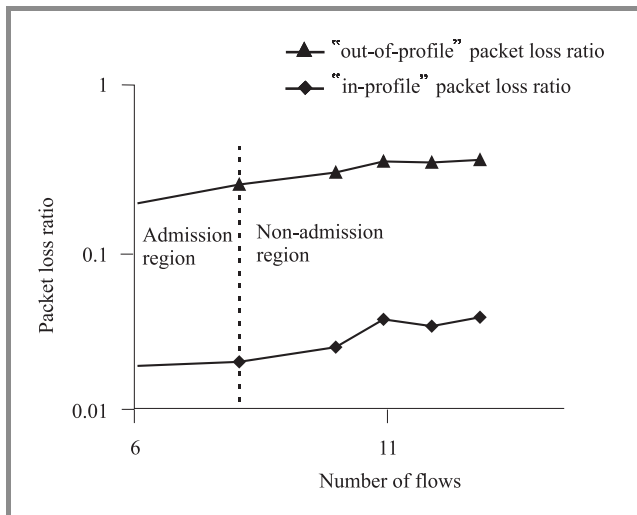


Fig. 12. “In-profile” and “out-of-profile” packet loss ratio versus number of TCP flows in PMM service.

connections. As it was expected, the packets conforming to the assumed traffic profile are delivered by the network with a significantly higher probability than the non-conforming packets.

Note that the proper configuration of WRED mechanism is crucial for flow differentiation inside the TCL3 class with

respect to the guaranteed throughput. Since there is high probability that the “out of profile” packets will be lost during network congestion, the TCP source sending “out-of-profile” traffic will likely be forced to decrease its sending rate. On the other hand, when the source transmits only conforming traffic, its packet loss rate will be much lower than in the previous case. This TCP source will not be forced to decrease its sending rate. Consequently, the average throughput of each PMM flow will be close to the SBR declaration.

#### 4.5. Premium missioncritical service

The PMC service was designed for short-lived non-greedy TCP flows, typically generated by transaction-oriented applications, e.g. database queries. The objective of this service is to provide high guarantee of packet delivery (low packet loss rate and relatively low packet transfer delay). In the following experiment, the test traffic was produced non-greedy TCP flows, transmitted between end-stations PC3 and PC1 (additionally for comparison this experiment was repeated with greedy TCP flows). Similarly as in the PMM service tests, the background traffic of CBR type was submitted to other NSs with the maximum possible rate. The capacity available for the tested TCL4 class was equal to 100 kbit/s.

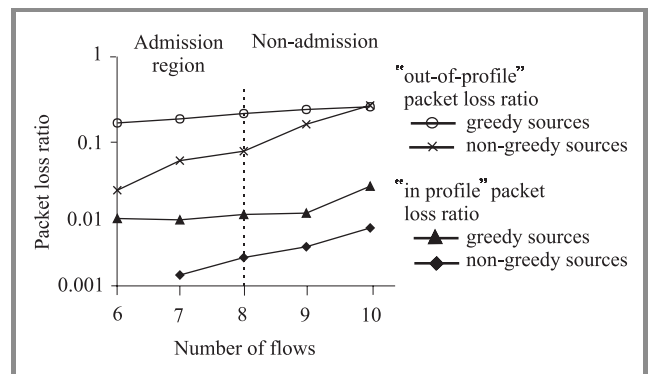


Fig. 13. “In-profile” and “out-of-profile” packet loss ratio versus number of greedy and non-greedy TCP flows in PMC service.

Figure 13 shows characteristic of packet loss ratio for “in-profile” and “out-of-profile” traffic as a function of number of running TCP connections (greedy or non-greedy). As one could expect, in the case of greedy TCP sources the packet loss ratio is significantly higher for both “in” and “out” packets. On the other hand, the observed packet loss ratio for non-greedy TCP flows is greater than the target value (fixed to  $10^{-6}$ ). Therefore, some modifications of queue management algorithm are required.

## 5. Conclusions

In the paper the approach for traffic engineering in the AQUILA QoS IP network was described. The measure-

ment experiments confirm that IP network with appropriate traffic handling mechanisms is capable to offer QoS guarantees with dynamic reservation scheme. The experiments carried out in AQUILA trial demonstrated the need for separation of streaming and for elastic traffic. Currently, AQUILA project defines 4 QoS NSs with different QoS objectives. Such approach allows efficient support of wide range of applications with different requirements. The obtained measurement results confirm that such approach can be implemented in practice, and that the AQUILA NSs generally provide the assumed QoS guarantees.

To guarantee QoS objectives appropriate AC algorithms should be employed. AQUILA project shows that the declaration based AC algorithms could guarantee the QoS requirements on the per flow basis in the IP network based on the DiffServ architecture. On the other hand, AQUILA AC algorithms assume the worst-case traffic patterns that are rarely met in practice. This sometimes can lead to low network resource utilization. Future work is focus on adding some measurements in the resource control algorithm for improving network utilization.

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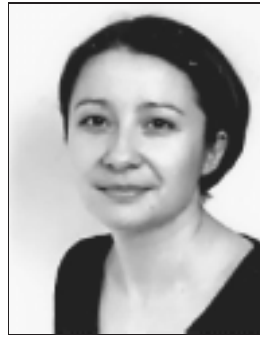
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