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# Predictive Flow-Aware Networks

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***Abstract*—Admission control routine in Flow-Aware Networks (FAN) may lead to severe fair rate degradation, which negatively impacts the performance of ongoing flows. To mitigate the problem, a predictive approach is proposed in this paper. Instead of waiting for the congestion to occur, proper admission control actions are performed when the system approaches the congestion state. After each network measurement, by analyzing the trend, the next values are predicted and actions are taken based on the predicted values. The proposed mechanism can be simultaneously used with the limitation mechanism providing a considerable performance increase.**

***Index Terms*—Flow-Aware Networks, FAN, predictions, service differentiation, QoS.**

## I. Introduction

Flow-Aware Networking (FAN) is a QoS architecture designed for the IP networks. The concept of FAN was initially introduced in [1] and, then, presented as a complete system in 2004 [2]. Its goal is to enhance the current IP network by improving its performance under heavy congestion. To achieve that, certain traffic management mechanisms to control link sharing are proposed, namely: measurement-based admission control [3] and fair scheduling with priorities [2], [4]. The former is used to keep the flow rates sufficiently high, to provide a minimal level of performance for each flow in case of overload. The latter realizes fair sharing of link bandwidth, while ensuring negligible packet latency for flows emitting at lower rates.

As the concept of FAN attracted a worldwide attention, many studies which enhance the architecture or propose new mechanisms have appeared. The problem of too long waiting times was resolved in [5] by providing the differentiated blocking scheme and by the flushing mechanism as proposed in [6], [7], and [8]. The notion of Multilayer Flow-Aware Networking (MFAN) was introduced in [9]. In [10], the authors compare admission control policies proposed for MFAN. [8] and [11] deal with failures and reliability issues in FAN networks. Finally, FAN is also a QoS architecture which fits into the network neutrality boundaries, as was shown in [12].

FAN intends to provide a minimum level of resources for each active flow. It does that by blocking new flows when congestion indicators exceed their fixed thresholds. It is assumed that those thresholds define the minimum level of service a FAN link is to assure. However, as shown in [13], this assumption cannot be made, as when many new flows arrive at the same instant, the thresholds are significantly exceeded.

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The root of the fair rate (FR) degradations in FAN lies in the very design of the admission control block. The key issue is the fact that admission criteria rely on the information delivered by the scheduling block which implies passive control. Only after the congestion is noticed, can admission control start to block new flows. Therefore, the minimum level of FR in FAN is not a guaranteed value, as proper actions happen after this boundary is crossed. The active approach would be to undertake measures before the congestion occurs.

One approach to resolve the FR degradation problem is to combat the consequences by limiting the number of flows that can be admitted in a certain time interval. This method, i.e., the limitation mechanism [13], provides good results and significantly improves the service assurance quality of FAN. The second approach, presented in this paper, is based on mitigating the reasons why the degradations occur in the first place. Therefore, the predictive mechanism is proposed which enables the admission control block to take preventive actions even before the congestion occurs. It is proved that the predictive mechanism can perfectly cooperate with the limitation mechanism providing best results.

The paper is organized as follows. Section II explains the operation of Flow-Aware Networking with special focus on the admission control functionality. Also the FR degradation problem is mentioned there. Next, Section III presents the concept of Predictive FAN showing possible setups and explaining the parameters needed to configure the mechanism. Section IV shows the performance of Predictive FAN evaluated through extensive simulation experiments. Finally, Section V concludes the paper.

## II. Operation of FAN

The goal of FAN is to enhance the perceivability of the current IP network by introducing a unique device, i.e., the Cross-Protect router. This device alone is responsible for providing admission control and fair queuing.

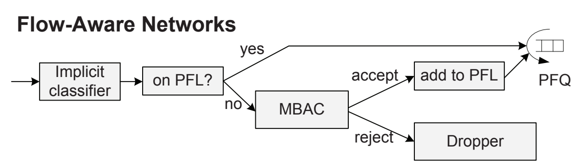


Fig. 1. Operation of FAN

Figure 1 illustrates the operation of FAN. All incoming packets are, firstly, classified into flows. The flow identification process is implicit and its goal is not to divide flows into different classes, but only to create an instance on which the service differentiation will be performed. Then, all the flows that are currently in progress, i.e., are present on the Protected Flow List (PFL) are forwarded unconditionally, whereas all new flows are subject to admission control. The admission control in FAN is measurement based which implies that the accept/reject decisions are based only on the current link congestion status. If a new flow is accepted, it is put onto the PFL list and then all forthcoming packets of this flow are forwarded without checking the status of the outgoing link by MBAC.

MBAC performs actions based on the information derived from the scheduling algorithms. Two parameters are constantly measured, i.e., fair rate (FR) and priority load (PL). Following [2], "fair rate is an estimation of the rate currently realized by backlogged flows", and represents the amount of link's bandwidth, which is guaranteed to be available for a single flow, should it be necessary. Similarly, "priority load is the sum of the lengths of priority packets transmitted in a certain interval divided by the duration of that interval", and shows the amount of data that is prioritized. The manner of calculating both indicators is a feature of the scheduling algorithm. Currently, there are two queuing algorithms designed for FAN networks: Priority Fair Queuing (PFQ) [2] and Priority Deficit Round Robin (PDRR) [4]. Additionally, a third scheduler based on the Approximate Fair Dropping algorithm was proposed in [14]. In the respective documents, a detailed description of all queuing disciplines, including pseudocodes, measured indicators and all required definitions may be found.

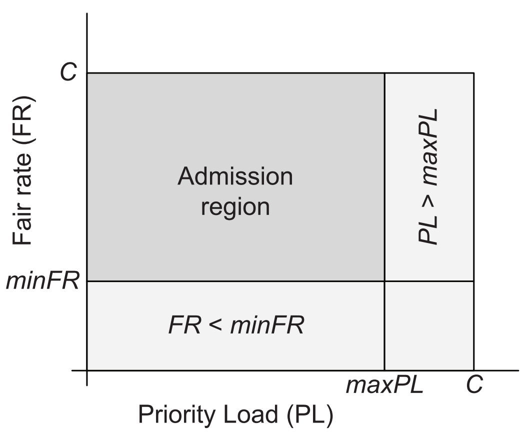


Fig. 2. Admission region in FAN

In the Cross-Protect router, the FR and PL estimators are fed to the admission control block which takes actions based on them. Figure 2 illustrates the admission decision in MBAC. Each router has two pre-defined threshold values of FR and PL which are to be maintained, namely: the minimum value of FR (minFR) and the maximum value of PL (maxPL). The idea behind those thresholds is that the system should be able to provide at least a minimum value of FR for each flow, and that the priority queue occupancy should not exceed maxPL to leave some room for the elastic flows. If the current FR is lower then minFR or if the current PL is greater than maxPL, the incoming flow is blocked. Otherwise, the link is in the admission region and a new flow is admitted. Therefore, those thresholds are, in fact, not guaranteed as blocking actions are taken only after those boundaries are crossed.

*FR degradations and limitation mechanism*

In theory, FR should be allowed to drop below the threshold only slightly before the admission control block starts functioning. Unfortunately, in practice, the FR drops might be significant. A similar situation concerns the second congestion parameter, i.e., the priority load. This problem, when combined with the heavy volume of incoming traffic, renders original FAN quality assurances ineffective in practice.

It was shown in [13] that frequent degradations of the FR may occur on FAN links when there are too many flows attempting to acquire the access to the link's bandwidth. To prevent those degradations, either FR needs to be measured more often, or some sort of limitations needs to be applied. However, the first option consumes much more router's CPU power which is undesirable. Limitations, on the other hand, hardly impact the computation power requirements while providing significant benefits.

The idea behind the limitation mechanism is that between any two consecutive measurements, only a limited, fixed number of new flows may be admitted. This approach protects the admission control block from over-admitting, i.e., from allowing too many new flows to acquire access to the link, which, consequently, degrades the FR. Through simulations, it was proved in [13] that reducing the inter-measurement time even 10 times does not provide better performance than introducing even a very simple limitation mechanism. This, essentially, means that increasing the frequency of measurements is a much worse option to mitigate the FR degradation problem than the limitations.

## III. Predictive approach

In this section, a predictive mechanism as an active approach to the realization of the admission control routine in FAN is proposed. Although the presented algorithms concern FR, identical approach can be applied to PL if necessary. However, FR is much more important congestion indicator in FAN, mainly due to the fact that FR is the estimation of the currently available bitrate for each flow. Therefore, it is extremely important to maintain the value of FR on a sufficient level.

In the FR prediction mechanisms, the admission control block tries to estimate the value of the next FR measurement and take proper actions based on the predicted FR, rather than on the current real measurements. In such a way, two actions can happen:

1) $FR > minFR$ and $expectedFR < minFR \implies$ MBAC will block new flows despite FR being over the threshold,
2) $FR < minFR$ and $expectedFR > minFR \implies$ MBAC will allow new flows despite FR being below the threshold.

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From the viewpoint of service assurance, the first action is more important, as it tries to preserve the minimum guaranteed FR. Therefore, two predictive mechanisms are defined: *half prediction* which utilizes the first action and *double prediction* which uses both. The following formula presents the method of estimating the next value of FR:

$$expectedFR = FR_t + p \cdot (FR_t - FR_{t-1}) \quad (1)$$

where: $expectedFR$ represents the predicted next value of FR, $FR_t$ is the measured FR in time $t$ and $p$ is the predictor. As FAN is a simple architecture, new mechanisms should not overcomplicate it. To implement the proposed scheme, the XP router needs to additionally remember the previously measured value of FR and the admission control routine needs to be altered, yet with no new functionalities. Based on this analysis, the prediction mechanism does not complicate the operation of FAN, while the mathematical formula to calculate the expected values is simple, therefore, very fast to compute.

Predictor $p$ is a number which tries to emulate the dynamics of the changes in the FAN link. This parameter is introduced as an adjustment factor to the mechanism. When $p = 1$, the difference between the current FR and the previous FR is calculated and this difference is added to the current FR. This way, the system assumes that the current FR tendency is constant. When the changes are more dynamic, especially on high-capacity links, the use of higher predictors might be more adequate.

## IV. Simulation experiments

To show the efficiency of the prediction mechanisms, a number of simulations were performed. The simulation scenario comprised of one 100 Mbit/s FAN link with user flows arriving with the intensity of, on average, 5 flows per second. The minFR parameter was set to 5% of the link capacity (5 Mbit/s) and was measured once every second. The volume of traffic to be sent by each flow was generated following the Pareto distribution (15 MB on average, shape factor: 1.5). The exponential distribution for generating the time intervals between the beginnings of the transmissions of the flows was used. The duration of each simulation run was set to 400 s.

Since each simulation run was started from the clean network state, the initial transient period was considered until the FR value reached the minFR threshold for the first time. All the data gathered in the transient period was disregarded. The simulations were repeatedly executed and 95% confidence intervals were calculated following the Student's t-distribution.

To present the problem numerically and to show how limitations can mitigate FR degradations, the mean deviation from the minFR threshold was defined as follows:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{|minFR - FR_i|}{minFR} \cdot 100\% \quad (2)$$

where $FR_i$ are the measured FR values over time. This parameter shows how much measured FR values differ from the minFR during the total measurement time (simulation time). As, in all cases, we simulate only the overloaded links, the ideal FR values should oscillate around the threshold and the deviation should be near zero. Great deviations mean that there are times in which end users receive much less bandwidth than the minimum FR, which is supposed to be guaranteed.

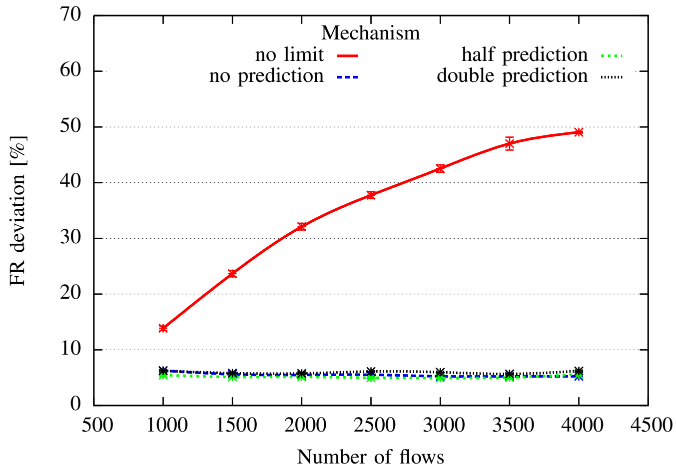


Fig. 3. FR deviation from minimum FR with respect to the number of active flows

Figure 3 shows the FR deviation from the minimum FR with respect to the number of active flows when different mechanisms are used. Here, the flow admission limit was set to 3 flows per measurement, and the predictor $p$ was set to 1. As can be observed, the prediction mechanism does not provide significantly lower deviations than standard static limiting mechanism (case: no prediction). It needs to be noted, however, that the deviations observed after the static limitation mechanism is applied are reduced to a completely acceptable level, making it hard to improve any further. The deviations are greatly reduced when compared to the case in which no limiting mechanism is used. Additionally, the deviations are independent of the volume of the carried traffic, represented by the number of active flows.

The deviations remained on the same level as when only static limitations were proposed, however, the amount of time in which FR drops below a certain level can be improved substantially. Table I shows how often does the measured FR drop below 95%, 90% and 80% of the minimum FR threshold. To compare the efficiency of the proposed mechanisms, the case when no limitations, and the case when simple limitation is performed are presented as well. From the numbers in Table I, we can see that the half prediction mechanism outperforms all the other approaches. The time in which FR drops below a certain threshold is shortened by 30-80% compared to the best case with static limitations. Given that static limitations offer drastic reduction of this time compared to the standard FAN routine, the result obtained by the half prediction mechanism must be considered as outstanding.

A little bit surprising is the fact that the double prediction mechanism does not provide improvement over static limitations. However, the reason behind such a behavior is twofold.

TABLE I
THE PERCENTAGE OF TIME IN WHICH FR DROPS BELOW 95% (A), 90% (B) AND 80% (C) OF THE MINFR THRESHOLD

| Mechanism | Number of flows | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 |
| 95% (a) | | | | | | | |
| no limitation | 68.73 ± 1.61 | 84.79 ± 0.72 | 89.30 ± 0.32 | 93.09 ± 1.54 | 92.17 ± 0.36 | 94.35 ± 0.33 | 94.79 ± 0.12 |
| no prediction | 35.92 ± 1.18 | 35.64 ± 1.29 | 31.43 ± 1.25 | 33.46 ± 1.78 | 33.18 ± 0.97 | 31.83 ± 1.12 | 30.91 ± 1.38 |
| **half prediction** | **23.94 ± 3.08** | **23.00 ± 2.64** | **23.43 ± 4.52** | **25.55 ± 1.34** | **24.52 ± 2.01** | **22.99 ± 2.34** | **24.89 ± 2.03** |
| double prediction | 37.37 ± 3.17 | 38.00 ± 1.51 | 36.60 ± 1.79 | 43.92 ± 1.72 | 41.05 ± 1.56 | 40.05 ± 2.38 | 43.68 ± 2.70 |
| 90% (b) | | | | | | | |
| no limitation | 53.61 ± 1.74 | 76.69 ± 0.65 | 85.00 ± 0.48 | 87.49 ± 0.33 | 89.01 ± 0.51 | 91.69 ± 0.96 | 92.29 ± 0.19 |
| no prediction | 13.90 ± 1.11 | 10.49 ± 0.85 | 8.89 ± 0.97 | 9.16 ± 0.84 | 7.97 ± 0.75 | 8.21 ± 0.76 | 7.58 ± 0.94 |
| **half prediction** | **3.97 ± 1.60** | **4.80 ± 0.60** | **5.04 ± 1.67** | **3.36 ± 0.63** | **3.12 ± 1.05** | **4.78 ± 1.25** | **6.11 ± 0.65** |
| double prediction | 13.14 ± 3.31 | 9.87 ± 1.23 | 11.88 ± 0.72 | 13.81 ± 1.35 | 11.52 ± 1.87 | 13.58 ± 1.47 | 17.53 ± 2.29 |
| 80% (c) | | | | | | | |
| no limitation | 24.62 ± 1.30 | 56.46 ± 2.11 | 72.73 ± 1.19 | 77.79 ± 0.54 | 82.42 ± 0.57 | 85.83 ± 0.93 | 84.84 ± 0.32 |
| no prediction | 0.10 ± 0.06 | 0.01 ± 0.03 | 0.01 ± 0.03 | 0.00 ± 0 | 0.00 ± 0 | 0.00 ± 0 | 0.00 ± 0 |
| **half prediction** | **0** | **0** | **0** | **0** | **0** | **0** | **0** |
| double prediction | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Firstly, as the FR deviation is on a level of a few percent, there is hardly any room for predicting the next values as the FR trend, as well as the over and under the threshold situation changes rapidly. Secondly, the fact that the admission control may admit new flows even when the current FR is below the threshold does not contribute to the reduction of the duration of FR drops.

Similar results are obtained when prediction mechanisms are compared to the static limitation mechanism under three different predictor values. Figures 4 and 5 show the mean deviation and FR drops duration, respectively. Here, the number of active flows is set to 1000 and the admission limit changes from 2 to 6 flows per FR measurement. The top plots show the double prediction mechanism, whereas the bottom ones present the half prediction mechanism. As can be observed, under the traffic pattern provided in the simulated scenario, the double prediction mechanism performs better when predictor $p$ is equal to 1. Still, the performance is worse than that obtained with the static limitation mechanism. This tendency is not visible in case of the half prediction mechanism. Here, both the FR deviation and the FR drops duration are slightly better than when no predictions are made, however, the relation between various predictors is unnoticeable.

This section shows that the double prediction mechanism does not provide the expected benefits compared to the static limitation mechanism. The half prediction scheme shows superior performance compared to the mechanism which already improves the admission control behavior in FAN. Compared to the original FAN routine, the gains from introducing the half prediction mechanism are substantial. The predictor is a factor which does not seem to have a significant impact on the performance of the half prediction mechanism, however, under different traffic characteristics, especially related to high-capacity links, the proper choice of the predictor might play an important role. This issue is to be evaluated in future.

## V. CONCLUSION

FAN is a QoS architecture that still needs some improvements or additional mechanisms to achieve optimum performance. Frequent degradations of FR may occur on FAN links when there are too many flows attempting to acquire access to the link's bandwidth. To prevent those degradations, either FR needs to be measured more often, or some new mechanisms need to be introduced. The first option, as explained, consumes much more router's CPU power which is undesirable. The second approach involves mechanisms such as the limitation mechanism [13] or the prediction mechanism.

The prediction mechanism which enhances the admission control routine in the FAN routers is presented and evaluated in this paper. It is shown that the FR deviation does not increase with the addition of the proposed mechanisms, whereas the amount of time in which FR drops below a certain thresholds is significantly, up to three times, reduced. The half prediction mechanism shows superior performance over the double prediction one, the reasons for which were also explained.

The simulations performed in [13] show that it is much better to introduce the limitations than to increase the frequency of measurement even 10 times. In this paper, it is shown that when the prediction mechanism is applied on top of the limitation mechanism, the performance increase is even more substantial. Comparing to standard FAN, the performance improvement is even more impressive. Finally, the proposed mechanisms are simple, and therefore, do not overcomplicate the overall architecture.

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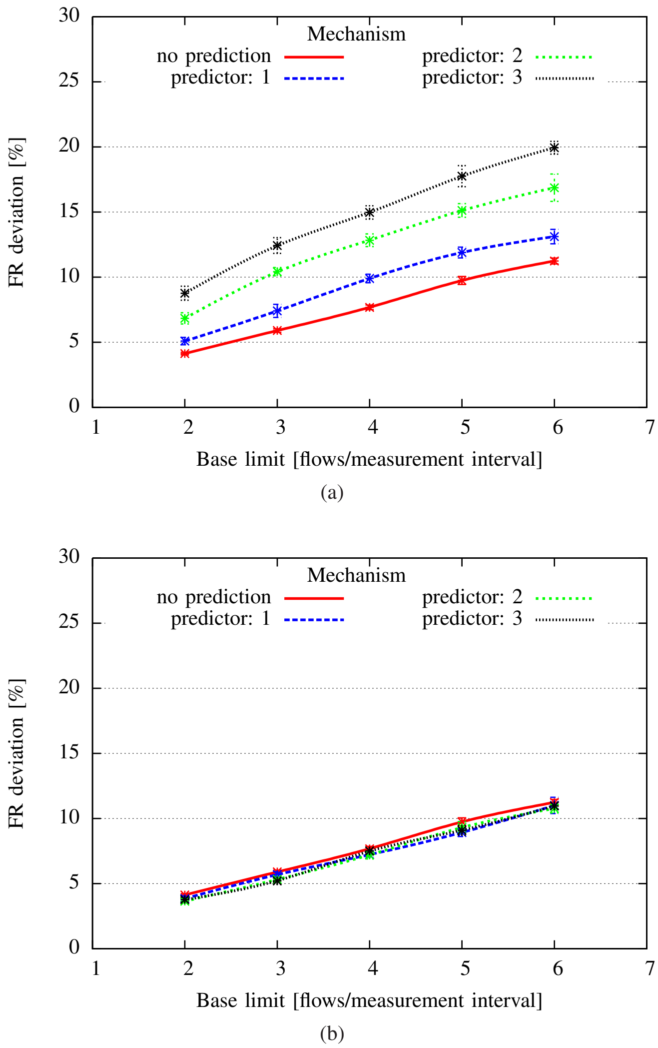


Fig. 4. FR deviation from minimum FR with respect to the admission limit and (a) double prediction, (b) half prediction mechanisms

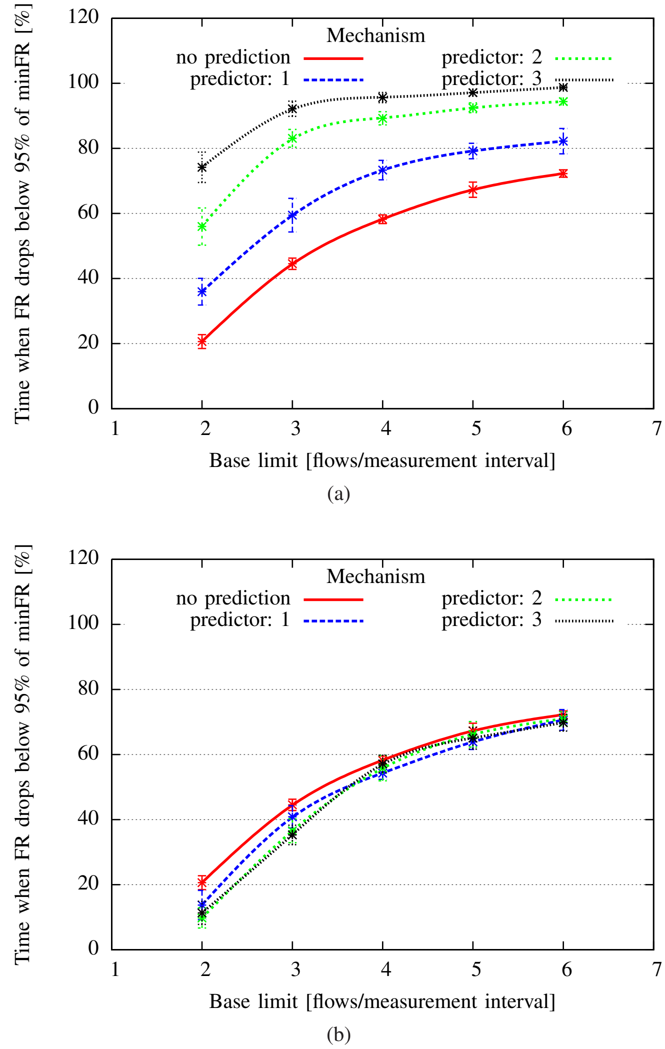


Fig. 5. FR deviation from minimum FR with respect to the admission limit and (a) double prediction, (b) half prediction mechanisms

## REFERENCES


[1] J. Roberts and S. Oueslati, “Quality of Service by Flow Aware Networking,” *Philosophical Transactions of The Royal Society of London*, vol. 358, pp. 2197–2207, 2000.

[2] A. Kortebi, S. Oueslati, and J. W. Roberts, “Cross-protect: implicit service differentiation and admission control,” in *Proc. High Performance Switching and Routing, HPSR 2004*, Phoenix, USA, 2004, pp. 56–60.

[3] S. Oueslati and J. Roberts, “A new direction for quality of service: Flow-aware networking,” in *Proc. 1st Conference on Next Generation Internet Networks - Traffic Engineering, NGI 2005*, Rome, Italy, 2005.

[4] A. Kortebi, S. Oueslati, and J. Roberts, “Implicit Service Differentiation using Deficit Round Robin,” in *Proc. 19th International Teletraffic Congress, ITC 2005*, Beijing, China, August/September 2005.

[5] A. Jajszczyk and R. Wojcik, “Emergency Calls in Flow-Aware Networks,” *Communications Letters, IEEE*, vol. 11, pp. 753–755, September 2007.

[6] J. Domzal and A. Jajszczyk, “New Congestion Control Mechanisms for Flow-Aware Networks,” in *Proc. IEEE International Conference on Communications ICC 2008*, Beijing, China, May 2008.

[7] ——, “The Flushing Mechanism for MBAC in Flow-Aware Networks,” in *Proc. 4th EURO-NGI Conference on Next Generation Internet Networks, NGI 2008*, Krakow, Poland, April 2008, pp. 77–83.

[8] J. Domzal, R. Wojcik, and A. Jajszczyk, “Reliable Transmission in Flow-Aware Networks,” in *Proc. IEEE Global Communications Conference GLOBECOM 2009*, Honolulu, USA, December 2009, pp. 1 –6.

[9] V. Lopez, C. Cardenas, J. A. Hernandez, J. Aracil, and M. Gagnaire, “Extension of the Flow-Aware Networking (FAN) architecture to the IP over WDM environment,” in *Proc. 4th International Telecommunication Networking Workshop on QoS in Multiservice IP Networks*, Venice, Italy, February 2008.

[10] J. Domzal, R. Wojcik, A. Jajszczyk, V. Lopez, J. Hernandez, and J. Aracil, “Admission control policies in Flow-Aware Networks,” in *Proc. 11th International Conference on Transparent Optical Networks, ICTON 2009*, Azores, Portugal, July 2009, pp. 1 –4.

[11] J. Domzal, R. Wojcik, and A. Jajszczyk, “The Impact of Congestion Control Mechanisms on Network Performance after Failure in Flow-Aware Networks,” in *Proc. International Workshop on Traffic Management and Traffic Engineering for the Future Internet, FITraMEn 2008*, Porto, Portugal, December 2008.

[12] ——, “QoS-Aware Net Neutrality,” in *Proc. The First International Conference on Evolving Internet, INTERNET 2009,*, Cannes, France, August 2009, pp. 147 –152.

[13] R. Wojcik, J. Domzal, and A. Jajszczyk, “Fair Rate Degradation in Flow-Aware Networks,” in *Proc. IEEE International Conference on Communications ICC 2010*, May 2010, pp. 1 –5.

[14] J. Domzal and A. Jajszczyk, “Approximate Flow-Aware Networking,” in *Proc. IEEE International Conference on Communications ICC 2009*, Dresden, Germany, June 2009.