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Chronology of the development of Active Queue Management algorithms of RED family. Part 1: from 1993 up to 2005

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Abstract. This work is the first part of a large bibliographic review of active queue management algorithms of the Random Early Detection (RED) family, presented in the scientific press from 1993 to 2023. The first part will provide data on algorithms published from 1993 to 2005.

Key words and phrases: active queue management, AQM, random early detection, RED, congestion control

1. Introduction

This work is a brief bibliographic review of algorithms of the Random Early Detection (RED) family, compiled according to the dates of publication of scientific works (articles and conference proceedings) in which the algorithms in question were presented to the public.

The authors do not claim that the prepared review includes all existing algorithms, but is the most complete of those published previously, since it includes bibliographic data on 240 algorithms.

Let’s briefly talk about other reviews that were published earlier, in which not only algorithms of the RED family were considered, but also other algorithms for active queue management.

The first of these works can be considered the article [1] published in 1995, although the term “active queue management (AQM) algorithms” was not used in it. Instead the term “congestion control algorithms” was used.

In the survey [1] the packet dropping policies for asynchronous transfer mode (ATM) and IP networks were discussed and compared in terms of fairness.

Another work [2], dated 1999, was the dissertation for the degree of Doctor of Philosophy, in which existing AQM algorithms (and in particular algorithms of the RED family) were analyzed, and ideas were formulated that allowed the development of new algorithms.

The following survey [3], published in 2003, was devoted to the aspects of congestion control with the emphasis on the active queue management. The such AQM problems as parameter tuning, insensitivity to input traffic load variation, mismatch between macroscopic and microscopic queue length behaviour and their implications were summarized and discussed. The attention was also paid to topics that are still relevant and open today: fairness, convergence and implementation complexity, interoperability and robustness, stability, assumptions of network dynamics and link characteristics.

In the 2004 survey [4] the AQM algorithms for responsive and unresponsive TCP flows and aggressive UDP flows were discussed and compared based on the fairness criterion. Also the classification, based on this criterion, for AQM schemes was proposed.

In the work [5], published in 2010, one of the authors of this review proposed the classification of RED algorithms according to different criteria (for example, the type of probability drop function, the type of queue function).

In the survey [6] published in 2013, the author tried to plot the development trajectory of active control algorithms from the first Random Early Detection (RED) algorithm in 1993 to the algorithms presented to the general public in 2011. The algorithms were classified according to various criteria and the general attributes of AQM schemes as well as the design approaches (for example, heuristic, control-theoretic and deterministic optimization) were presented.

In 2016 the comprehensive review of fairness-driven queue management algorithms was presented in [7] with a new taxonomy of categorizing fairness-driven queue management algorithms. The design approaches and key attributes were discussed, compared and analyzed.

Among the works of the last three years in which various algorithms are analyzed and compared, it is worth mentioning the following [8–10].

The review is structured as follows. The structure of the work is as follows. Each section is dedicated to one year, and it presents algorithms of the RED family, scientific publications (articles in scientific journals, conference proceedings, technical reports, etc.) on which were presented this year. In Section 12 the authors discussed the results and the future research directions are highlighted.

2. 1993

This year, the work [11] was published in which the classical Random Early detection (RED) algorithm was presented.

The classic RED (random early detection or random early discard or random early drop) is a queueing discipline with two thresholds ($Q_{\min}$ and $Q_{\max}$) and a low-pass filter to calculate the average queue size $\hat{Q}$ [11]:

$$\hat{Q}_{k+1} = (1 - w_q)\hat{Q}_k + w_q\hat{Q}_k, \quad k = 0, 1, 2, \ldots, \tag{1}$$

where w_q, $0 < w_q < 1$ is a weight coefficient of the exponentially weighted moving-average and determines the time constant of the low-pass filter. As said in [11] RED monitors the average queue size and drops (or marks when used in conjunction with ECN) packets based on statistical probabilities $p(\hat{Q})$:

$$p(\hat{Q}) = \begin{cases} 0, & 0 \leqslant \hat{Q} < Q_{\min}, \\ \dfrac{\hat{Q} - Q_{\min}}{Q_{\max} - Q_{\min}} p_{\max}, & Q_{\min} \leqslant \hat{Q} < Q_{\max}, \\ 1, & \hat{Q} \geqslant Q_{\max}, \end{cases} \tag{2}$$

$p_{\max}$ — the fixed maximum value of drop (marking) probability if the threshold $Q_{\max}$ is overcome.

Analysis and criticism of proposed AQM algorithm are presented in the works [12–18].

Suggestions for tuning and optimizing the key parameters of the algorithm are proposed in the following works [19–30]. The implementation of RED in the Next Generation Passive Optical Network (NG-PON) was presented in [31].

Further modifications of the RED algorithm consisted, as a rule, either in changing the number and/or value of thresholds, or in changing the type of drop function (a single linear function was replaced by several linear or nonlinear ones, or combinations of linear and nonlinear functions), or in replacing the average queue size $\hat{Q}$ by the current (instant) queue size q, either in the simultaneous use of the average $\hat{Q}$ and current q queue lengths, or in the dynamic change of one or several parameters (threshold values $Q_{\min}$ and $Q_{\max}$, maximum drop probability $p_{\max}$) depending on control parameters (queue size, incoming rate, rate of queue size change), or in the use of methods of fuzzy logic, Q-learning, neural networks to determine the optimal algorithm parameter values.

The changes also affected whether the new algorithm was being developed to manage a single incoming traffic flow or multiple incoming flows with different priorities.

3. 1997

The development of RED for several flows — Fair RED [32] or Flow RED [33] was introduced in 1997. It uses per-active-flow accounting to impose on each flow a loss rate that depends on the flow's buffer use.

The idea of adaptive active queue management algorithms which may reduce loss rates for congested links was formulated in [34] (as Adaptive RED) and further developed in [35]. The main idea was to adapt $p_{\max}$ of RED in order to keep the average queue size between thresholds $Q_{\min}$ and $Q_{\max}$.

4. 1998

The first Recommendations on Queue Management and Congestion Avoidance in the Internet was given in [36].

RIO (RED with In|Out) algorithm was introduced in [37]. The core of the idea was to monitor the traffic of each user as it enters the network and tag packets as either *in* or *out* based on their service allocation profiles, then at each congested router, preferentially drop packets that are marked as being *out*. RIO used the same drop mechanism as in RED but is configured with two sets of parameters ($p_{\max}$, $Q_{\min}$ and $Q_{\max}$), one for *in* packets and one for *out* packets. Among the other works devoted to modeling, performance analysis and optimal tuning of the algorithm parameters, the following scientific publications [38–41] should be mentioned.

The modifications of RIO algorithm — RIO-C (RED with In|Out and Coupled Virtual Queues) and RIO-DC (RED with In|Out and Decoupled Virtual Queues) are described in [42] and the comparison of these algorithms with the algorithm WRED (1999) in terms of drop of packets is given in [43].

Fair-buffering random early detection (FB-RED) algorithm was presented in [44] to solve the problem of unfairness among links. Although FB-RED results in fairness among links, it however needs to track the information for all the links.

The Fair RED algorithm, which relies on usage of buffer spaces by the different flows (per-active flow accounting) to determine the drop rate of the each flow, was presented in [45]. Although it achieves a fair drop rate for different flows, it needs to track the state of each flow which results in scalability problems similar to those in [44].

5. 1999

Weighted Random Early Detection (WRED) algorithm was introduced by Cisco and the specification can be seen in [46] (or in Cisco IOS Quality of Service Solutions Configuration Guide, Release 12.2 [47]) and was one of the predominant AQM scheme implemented. The algorithm WRED is an extension to RED and was designed to handle traffic of various priorities. In this algorithm, for each type of traffic, its own sets (coinciding or not coinciding) of control parameters are specified (threshold values $Q_{\min}$ and $Q_{\max}$, parameter $p_{\max}$)). The modifications of WRED are Distributed WRED (DWRED), which is the Cisco high-speed version of WRED [47], and Flow-Based WRED (forces WRED to afford greater fairness to all flows on an interface in regard to how packets are dropped) [47]. The other works on WRED are [43, 48–52].

In [53] two versions of RIO algorithm were introduced: (r,RTT)-adaptive RIO algorithm and dynamic RIO (DRIO) algorithm. In [54] DRIO was applied to aggregated traffic instead of the individual flows as in [53].

In [55] to solve the scalability problem of FB-RED [44] and FRED [45] the Stabilized RED (SRED) was introduced. SRED like RED discards packets with a load-dependent probability when a buffer in a router seems congested and stabilizes the buffer occupation at a level independent of the number of active connections by estimating the number of active connections (flows).

In [56, 57] Balanced RED (BRED) algorithm that drops packet preventively in order to actively penalize the non-adaptive traffic that attempts to "steal" buffer space, and therefore bandwidth from the adaptive traffic flows, was presented.

In [58] Class-Based Threshold RED (CBT-RED) algorithm was presented in order to reduce congestion in routers and to protect TCP from all UDP flows while also ensuring acceptable throughput and latency for well-behaved UDP flows. This algorithm sets the $Q_{\min}$ and $Q_{\max}$ thresholds according to the traffic type and its priority.

A RED discard strategy for ATM networks (ATM-RED) was introduced in [59].

In [60] the Refined RED (Re-RED) algorithm was proposed in order to prevent buffer overflow at a gateway, the RED framework was refined in such a way that the gateway can detect a transient congestion in a timely manner and take actions to quench it when the queue is near full.

In [61] the idea of adaptive active queue management algorithms, started in [34], was continued (Self Configuring RED). The dependence of the effectiveness of RED on the appropriate parameterization of the RED queue was shown. It was proved that there were no single set of RED parameters that work well under different congestion scenarios. As a result the authors proposed and experiment some adaptive RED gateways which self-parameterize themselves based on the traffic mix.

In [62] the modification of RED probability drop function was proposed. The linear drop function has been replaced by a parabolic one, so the new algorithm is called Parabolic RED (PRED). This algorithm was implemented in Cisco routers.

6. 2000

The Gentle RED algorithm (GRED), based on ideas from [59], was proposed by Sally Floyd in [63] and the double maximum threshold parameter was introduced in order to overcome the limitations of the RED algorithm. The comparison of tail drop and active queue management RED and GRED algorithms performance for bulk-data and Web-like Internet traffic was conducted in [64]. In [65] the performance GRED (Gentle RED), DRED (Dynamic-RED) [66] and SRED (Stabilized RED) [55] was analyzed. It was clarified how the performance of AQM mechanisms (such steady state performance measures as the average queue length and the packet loss probability) is affected by a setting of control parameters. In [67] the discrete-time queuing model of GRED algorithm was considered. The performance analysis of GRED (as well as other active queue and passive queue management algorithms) for multi-hop wireless relay networks was presented in [68]. The gentle parameter of GRED was reconsidered in [69].

Weighted RED with Thresholds (WRT) as the development of Weighted RED (WRED) [46] was introduced in [70] and compared with classicsl WRED and RED In and Out (RIO) [37] algorithms.

The Gentle RED algorithm with instantaneous queue size (GRED-I) (instead of exponentially weighted average queue size as in GRED) was proposed in [71].

The modification of RIO [37] algorithm called RI+O was presented in [72] to reduce the effect of an inadequacy in the packet differentiation (between high-profile flows and low-profile flows) RIO algorithm used in the Diff-Serv routers.

The congestion algorithm that uses fuzzy logic based control theory (Fuzzy RED) in order to achieve finer tuning for packet discarding behaviours for individual flows and to provide better quality of service to different kinds of traffic was introduced in [73]. The revised version of [73] is [74]. Fuzzy logic based approach for more predictable congestion control implementation within the DiffServ architecture was presented in [75, 76].

A Rate Based RED Mechanism (Rb-RED) that reduce the number of RED parameters to only one was introduced in [77]. The basic idea of this algorithm is that the packet drop probability was defined as a function of the long-term average arrival rate.

The Double Slope RED (DSRED) as the active queue management scheme for next generation networks (homogeneous TCP/IP networks) was described in [78]. It was proposed to use the two segment drop function and three thresholds instead of the single segment linear drop function with two thresholds as in RED [11] and dynamically change the slope of the packet drop probability curve based on the level of congestion in the buffer. The case of heterogeneous networks and DSRED was considered in [79]. The other works on DSRED are [80] and [81], where the influence of the way packets were chosen to be dropped (end of the tail, head of the tail) on the response time was investigated.

Random Early Adaptive Detection RED/ECN (READ) algorithm as an adaptive queue management scheme for maintaining of high throughput and low round-trip delays under dynamic traffic loads was introduced in [82].

7. 2001

The Adaptive RED (ARED) algorithm, based on ideas from [34] and [61], was proposed by Sally Floyd, Ramakrishna Gummadi and Scott Shenker in [35]. Some algorithmic modifications, while leaving intact the basic Feng idea of $p_{\max}$ adaption in order to keep the average queue size between thresholds $Q_{\min}$ and $Q_{\max}$, were made. The proposed version of RED algorithm, according to the authors, removed the sensitivity to parameters that affect RED's performance and could reliably a specified target average queue length in a wide variety of traffic scenarios. The main differences from the proposed algorithm were the following:

1) $p_{\max}$ was adapted to keep the average queue size within a target range half way between $Q_{\min}$ and $Q_{\max}$;
2) $p_{\max}$ was adapted slowly, over time scales greater than a typical round-trip time, and in small steps;
3) $p_{\max}$ was constrained to be within the range $[0.01; 0.5]$;

4) for $p_{\max}$ an additive-increase multiplicative-decrease (AIMD) policy was used instead of multiplicative-increase and multiplicative-decrease (MIMD) policy.

The tuning of ARED parameters was considered in [83–85]. The ARED comparison with other algorithms was presented in [86–88].

Dynamic RED (DRED) algorithm, which randomly discards packets with a load-dependent probability when a buffer in a router gets congested so a router queue occupancy is stabilised at a level independent of the number of active TCP connections, was introduced in [66]. The comparison of the DRED algorithm with GRED [63] and [55] was carried out in the work [89]. The comparison of DRED algorithm with other algorithms that do not belong to the RED family is presented in [90]. The analytical discrete-time queuing models of DRED algorithm were developed in [91, 92].

The Modified RED (MRED) algorithm computing the packet drop probability based on the heuristic method was presented in [93]. MRED controls queue by using packet loss information and link utilization history information with small queue size. The simulation results presented by authors proved MRED ability to improve fairness, throughput and delay.

The Least Recently Used Cache RED (LRU-RED) algorithm introduced in [94] empowers the routers to contain high bandwidth flows at the time of congestion. Also this algorithm lowers the drop probabilities of short-lived flows and also of responsive high bandwidth flows.

In [95] the new version of RED algorithm — RED-PD (Random Early Detection-Preferential Dropping) was proposed. This algorithm controls the throughput of the high-bandwidth flows by using the packet drop history at the router in order to detect these flows in times of congestion and preferentially drop packets from them.

8. 2002

Rate-based RIO (Rb-RIO) algorithm [96] is an extension of Rate-based RED [77] for traffic with different priority classes (MPEG video stream), so the main idea of RIO [37] was used. The proposed algorithm was compared with Drop-Tail and RED in terms of transport layer throughput, system fairness, application layer throughput and video stream quality.

Extended drop slope random early detection (ExRED) [97] was proposed in order to overcome such RED mechanism problems as low throughput achievement and high number of consecutive drop. The main idea was to modify the drop probability function as a second order polynomial function of the average queue size $\hat{Q}$ in order to keep packet drop rate increasing smoothly but continue with a higher rate when the queue size is more closed to the limit of buffer size ($\hat{Q} \geqslant Q_{\max}$).

In order to improve fairness in high-speed networks the EASY RED algorithm was developed in [98]. It was proposed to use the instantaneous queue size and the single threshold $Q_{\min}$ instead of average queue size and two thresholds ($Q_{\min}$ and $Q_{\max}$) as in RED [11], also the drop probability was defined as a constant when the instantaneous queue length is greater or equal to $Q_{\min}$.

Multi-class RED (MRED) algorithm for several classes of traffic (each traffic class may comprise a number of flows) was introduced in [99]. For each class of traffic, its own set of RED parameters (maximum drop probability and the minimum and maximum thresholds) were specified, which can either coincide or differ.

In [100] for Active RED (ARED, AcRED) algorithm it was proposed to use the heuristic method instead of static one for parameters setting.

In order to improve overall QoS support at the router by satisfying the average performance requirements of incoming packets in terms of throughput and delay in [101] the extension of Adaptive RED (ARED) [35] called RED-Worcester was introduced. The RED-Worcester algorithm based on queuing delays provides a moving target queue size instead of fixed target queue size in ARED, so, when incoming traffic is mostly throughput-sensitive, RED-Worcester tries to maintain a higher average queue to improve the overall throughput, or, when incoming traffic is mostly delay-sensitive, RED-Worcester tries to lower the average queue size to reduce the average queuing delays.

9. 2003

In [102] the new version of Adaptive RED [34, 35], also called Adaptive RED (A-RED), was introduced. It was proposed to adaptive vary not only the maximum packet drop probability $p_{\max}$ (as in [34, 35]), but also the weight coefficient of the exponentially weighted moving-average w_q. As a result the improvement in terms of packet loss rates and queue stability without adversely affecting the link utilization was achieved.

In [103] the flow-based congestion control scheme, called RED with dual-fairness metrics (DRED), was proposed in order to dissolve the unfairness per flow and so provide a feasible QoS. DRED explicitly considers both the instantaneous (the amount of network resources that each flow occupies at the considered time) and the historical (the amount of network resources that each flow has consumed up until the considered point of time) use of network resources for the purpose of dissolving unfairness per flow within the same class, and thereby improving the throughput of each flow.

In [104] the new version of Adaptive RED [35] scheme — Proportional derivative RED controller (PD-RED), based on the proportional derivative (PD) control principle, was introduced.

In [105] the new adaptive fuzzy-based control RED algorithm (AFRED) was designed. This algorithm computes the packet drop probability according to pre-configured fuzzy logic by using the instantaneous queue size as input variable. The ability to dynamically readjust the fuzzy rule in order to make AFRED itself extensively stable for many dynamic environments was also introduced.

The new version of RIO (RED with In|Out) [37] with the ability of self-configuring out-of-profile thresholds, called Adaptive-RIO (A-RIO), was developed in [106]. The main objective of Adaptive-RIO was to increase best-effort throughput by utilizing the available buffer spaces of the core routers in DiffServ networks.

The combination of the Adaptive RED (A-RED) algorithm [35] and the RIO-C algorithm [42], suitable for building an Assured Forwarding (AF) per-hop behaviour (PHB), was proposed in [107] for solving the following tasks: the simplification of the configuration of DiffServ-enabled routers by alleviating the parameter settings problem; the automatic translation a delay parameter into a set of router parameters, the stabilization of the queue occupation around a target value under heavy network load, irrespective of traffic profile. The further study of the proposed algorithm was carried out in [108].

10. 2004

Another version of the Adaptive RED algorithm [35], working with joint co-operation between sources and network routers and therefore called Dynamically Adaptive RED (DARED), was presented in the work [109]. The aim of this algorithm was to guarantee the distribution of the available network resources to flows of different classes with different declared QoS requirements.

The Modified Random Early Detection (MRED) algorithm, designed to provide better control over the burstiness level, was presented in [110]. The proposed modification was that the drop function (probability) takes into account not only the average queue size $\hat{Q}$, but also the instantaneous queue size Q (the incoming packet is dropped if $\hat{Q} > Q_{\max}$ and $Q > Q_{\max}$).

The algorithm, called Priority Random Early Detection (PRED), was described in [111] for different priority types of traffic, and for each type of traffic, its own set of control parameters is set, which can dynamically change values depending on network load.

The new AQM scheme, Short-lived Flow Friendly RED (SHRED), targeted at providing better network performance for short-lived Web traffic, was presented and analyzed in [112]. Using an edge hint to indicate the congestion window size in each packet sent by the flow source or by an edge router, SHRED preferentially drops packets from short-lived Web flows (flows with small TCP windows) with a lower probability than packets from long-lived flows (flows with large TCP windows). Thus SHRED protects short-lived flows from low transmission rates, and provides fairer bandwidth allocation among flows.

The development of Flow RED algorithm [33] — RED with Dynamic Thresholds (RED-DT), was proposed in [113]. This algorithm dynamically adapts queue parameters to achieve a more fair distribution of the link capacity. In order to identify unresponsive and greedy flows, RED-DT maintains per-flow state for active flows. Flow is considered to be active if it has at least one packet in the queue. For each active flow, there is an entry in a flow table that contains the instantaneous queue size Q_i, average queue size $\hat{Q}_i$ and maximum drop probability $p^i_{\max}$. Similar to RED, RED-DT maintains minimum and maximum thresholds $Q_{\min}$ and $Q_{\max}$, but these thresholds are dynamically changed upon each packet arrival.

In [114] the modification of the classic Random Early Detection (RED) algorithm [11] with hyperbolic drop function instead of linear one (RED) was introduced.

In [115, 116] two versions of Adaptive RIO algorithm [107] were presented: ARIO-D (Adaptive RIO for Delay) and ARIO-L (Adaptive RIO for Loss). The first algorithm (ARIO-D) takes specific average queue length range as control target, keeps $Q_{\max}$ as constant and adaptively adjusts $p_{\max}$ for *out*-packets to meet the expected steady state. The second algorithm (ARIO-L) takes specific loss ratio range as control target, for *out*-packets keeps $p_{\max}$ as constant and adaptively adjusts $Q_{\max}$ to meet the expected steady state.

The new RED scheme, called Loss Ratio Based RED (LRED), which measures not only the queue size, but also the latest packet loss ratio, and uses both these parameters in order to dynamically adjust packet drop probability, was presented in [117]. The further development of this algorithm is presented in [118].

The Class-Guided RED (CGRED) algorithm was introduced in [119]. In CGRED the packet drop operation is developed into a class-differential one by introducing a couple of class-specific adjusting decisions or guidelines: the adjustment direction (whether to increase or decrease or just maintain the RED drop probability) and the guiding probability (the intensity of the given adjustment). Thus the RED packet drop probability calculated is considered as a reference value and the guiding probability is considered as a limiting bound for choosing the actual dropping probability.

The Proxy-RED algorithm [120] was proposed as a solution for reducing the AQM overhead from the access point and as a development of ARED [34, 35]. The average queue size in Proxy-RED is calculated periodically but not at the moment of each packet arrival as in RED [11] or ARED [34, 35]. Also the modifications for drop probability function were made. The development of Proxy RED was presented in [121].

11. 2005

In [122] the Exponential-RED (E-RED) AQM (Active Queue Management) algorithm, as a decentralized network congestion control algorithm with dynamic adaptations at both user ends and link ends, was presented. In this algorithm the packet dropping probability was set as the exponential function of the virtual queue length and the capacity of the virtual queue was slightly smaller than the link capacity. E-RED was the first AQM schema for which the ability to stabilize TCP-Reno for a general topology network with heterogeneous delays has been proven. For a TCP-Reno network with Exponential-RED control, a discrete-time dynamical feedback system model with delay was studied in [123].

In order to maximize the throughput and to minimize the packet drop and delay the new algorithm — Adaptive RED with Dynamic Threshold Adjustment (ARDTA) was introduced in [124]. For this algorithm the thresholds were dynamically modified by using an exact expression of average queue size for a given burst size and number of nodes. The minimum threshold $Q_{\min}$ was set by an expression for a given burst size, the maximum thresholds $Q_{\max}$ was changed dynamically based on traffic conditions and buffer size with also taking into account the burst size. The assumption was made that the maximum threshold $Q_{\max}$ would be reached when the instantaneous queue size was equal to the maximum buffer size. The other work on this algorithm is [125].

Piecewise Linear RED (PL-RED) [126] is the modification of Gentle RED (GRED) [63]. In this algorithm the drop probability function was a piecewise linear function with $N = 5$ segments.

The another variant of Gentle RED (GRED) [63] — Adaptive Exponential RED (AERED), was also presented in [126], where the drop probability function was an exponential function with parameter β depending on average queue size and thresholds and p (the amount of concavity of an exponential function).

The dynamic modification of Weighted RED (WRED) [46, 47] was proposed in [127] and was called as Dynamic Weighted RED (DWRED). For this algorithm the TCP Window-Aware Marker (TWAM) was introduced for distribution of the resources available for the total traffic of an AF FEC (Assured Forwarding Forward Equivalence class) among the individual AF FEC flows in a fair manner. Based on TWAM the thresholds and $p_{\max}$ are dynamically configured. So the proposed WRED configuration mechanism responds to fluctuations in available resources, allowing the use of excessive resources whenever they are available, in a way that achieves a bounded average queuing delay for packets.

The Revised version of Adaptive RED [35] — RARED, was described in [128]. To alleviate the effect of w_q the RARED takes the input rate besides queue occupancy into account to detect significant changes in the network's condition.

The multi-class signaling overload control algorithm (Signaling RED — SiRED) for telecommunication switches as a modified version of WRED [46, 47] was proposed in [129]. SiRED measures the system load using queue lengths.

The modification of RED [11], based on game theory, for Internet switching with selfish users was presented in [130]. The new algorithm was called as Preemptive RED (PRED). The main feature of PRED is extra drop mechanism that drops an additional packet of the same user from the buffer when its packet is dropped by RED in order to penalize users that do not respond to congestion signals.

Subsidized RED (SubRED) algorithm, designed for short-lived (fragile) flows (e.g. most HTTP flows) in order to keep the link utilization high while reducing the average flow response time, was proposed in [131]. Subsidized RED (SubRED) identifies short-lived flows that have recently lost packets and/or are in their slow start phases, and protects them from being further punished unnecessarily for a short duration of time (flow subsidy).

The burst-sensitive RED algorithm for GPRS links in a heterogeneous mobile environment was presented in [132] and was called Burst-sensitive RED (BSRED). The new parameter to the classic RED [11] was added — Burst Threshold B_t, which represents the threshold of the number of consecutive packets en-queued (B_p) without a packet de-queued. Thus the new rule was added to the RED algorithm: on each packet's arrival, if $B_p \geqslant B_t$, a packet will be dropped, irrespective of the current queue length. In addition, B_p is reset to zero only when there is a packet de-queued. That is, incoming packets are continually dropped if there is no packet de-queued once $B_p \geqslant B_t$.

The nonlinear version of ARED [35] with nonlinear power packet dropping probability function was proposed in [133] and called as POWer Adaptive

Random Early Detection (POWARED). In order to enable POWARED to cater for dynamics of bursty network traffic and intelligently differentiate between levels of congestion occurred, the decrement or increment adjustment was based on the ratio of deviation between current average queue size and target queue size (steady-state queue size).

The virtual queue management approach, named Virtual Queue RED (VQ-RED, VQRED) to address the fairness problems (downlink/uplink fairness and fairness among flows in the same direction) was introduced in [134]. VQ-RED treats all the competing flows (uplink flows and downlink flows) fairly through managing their corresponding virtual queues. It punishes the arbitrary flows and gives more benefits to the weak flows. In this way it guarantees the fairness among the flows.

12. Conclusions

The presented bibliographical chronological review of active control algorithms of the RED family is the most complete both in terms of the number of algorithms reviewed (more than two hundred) and in terms of the number of scientific publications analyzed and presented. This review will be useful to researchers in the field of the congestion control.

Active queue management algorithms of the RED family are not something new for the authors of this work, as evidenced by the publications presented below [5, 135–142].

In the future, the authors plan not only to classify the considered algorithms based on the classification criteria presented in [5–7], but also to review and classify other active queue management algorithms.

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Хронология развития алгоритмов активного управления очередями семейства RED. Часть 1: 1993–2005

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Аннотация. Статья является первой частью большого библиографического обзора по алгоритмам активного управления очередями, относящимся к семейству алгоритмов случайного раннего обнаружения (RED), представленных в научной печати с 1993 по 2023 года. В первой части приведены данные по алгоритмам, опубликованным с 1993 по 2005 года.

Ключевые слова: активное управление очередями, AQM, RED, управление перегрузками