



Chronology of the development of Active Queue Management algorithms of RED family. Part 2: from 2006 up to 2015

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Abstract. This work is the second 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. This part provides data on algorithms published from 2006 to 2015.

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

1. Introduction

This work is the second part of the 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 first part was presented in [1].

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.

The characteristics of the RED algorithm are the following:

- The algorithm is extremely simple.
- The algorithm is designed to use as few computing resources as possible.
- The main computational complexity comes from calculating the reset (drop) function.
- Due to the use of a moving average in the algorithm, RED handles burst traffic well.
- In TCP/IP networks, the RED algorithm helps eliminate the global synchronization problem. It occurs when multiple sources operating over the same congested network segment experience packet loss. As a consequence, these sources simultaneously reduce the speed and then (also simultaneously) gradually increase it, which leads to new congestion, packet loss and repetition of the entire procedure. The network state periodically changes from idle to overloaded.
- RED allows to avoid global synchronization by selectively destroying packets from specific sources.

The mathematical model of RED-type algorithms is quite complex, so it is extremely problematic to substantiate the influence of different elements of the algorithm on the quality of its work.

The key disadvantage of RED, which many experts report, is the lack of a strict algorithm for setting RED parameters [2]. The RED parameters set:

- thresholds;
- reset (drop) function form;
- buffer size.

Changing some parameters immediately affects others.

Modifications of the RED algorithm consisted, as a rule, either in changing the number and/or value of thresholds (multiple thresholds to define different functions on different segments may be used for this purpose), 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, in order to obtain the behavior as desired under the default configuration), 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.

Since quite a lot of similar functions can be specified (with minimal effort), and there is no adequate mathematical model yet, research to improve RED will continue indefinitely.

The review is structured as follows. Section 2 provides a brief description of the RED algorithm. Each subsequent 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 13 the authors discussed the results and the future research directions are highlighted.

2. The classic RED algorithm

In 1993 the classical Random Early detection (RED) algorithm was introduced in [3].

The classic RED algorithm 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} [3]:

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

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 [3] RED monitors the average queue size and drops (or marks when used in conjunction with ECN) packets based on statistical probabilities $p(\hat{Q})$:

$$p(\hat{Q}) = \begin{cases} 0, & 0 \leq \hat{Q} < Q_{\min}, \\ \frac{\hat{Q} - Q_{\min}}{Q_{\max} - Q_{\min}} p_{\max}, & Q_{\min} \leq \hat{Q} < Q_{\max}, \\ 1, & \hat{Q} \geq Q_{\max}, \end{cases} \quad (2)$$

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

The principles of RED work:

- RED tracks the average queue size and dropped packets based on statistical probability;
- RED can also use ECN mark tracking;
- if the buffer is almost empty, then all packets are passed through as normal;
- as the queue begins to grow, the probability of packets being dropped also begins to increase;
- when the buffer is completely full, the probability becomes one and all incoming packets are discarded;
- we can say that when a router's buffer fullness exceeds some threshold value, the probability of dropping an incoming packet depends on the extent to which this threshold value is exceeded.

Analysis and criticism of proposed AQM algorithm are presented in the works [2, 4-9].

Suggestions for tuning and optimizing the key parameters of the algorithm are proposed in the following works [10-21]. The implementation of RED in the Next Generation Passive Optical Network (NG-PON) was presented in [22].

3. 2006

The State Dependent Random Early Detection (SDRED) algorithm [23] to improve delay and jitter performances by adjusting such RED parameters the maximum threshold Q_{\max} and queue weight w_q to four different levels according to queue status.

In [24] the new Active Queue Management algorithm for 3G Radio Network Controllers, called Time-to-live based RED (TTLRED), was introduced and compared with three other AQM mechanisms: RED [3], ARED [25] and Packet Discard Prevention Counter (PDPC) [26]. Two version of TTLRED were given. The first one is TTLRED for incoming packets, where the averaged queue size in the Gentle RED algorithm [27] was replaced with a packet lifetime and the drop counter was also modified (only every N -th packet can be dropped even if the Q_{\max} is exceeded. The second version is TTLRED for buffered packets, where packets were given a random dropping (or marking) time while entering the PDPC buffer.

In Nonlinear RED (NLRED) algorithm [28] in order to make the packet dropping function more flexible (packet dropping becomes gentler than RED at light traffic load but more aggressive at heavy load) it was proposed to replace the linear packet dropping function in RED [3] by a judiciously designed nonlinear quadratic function and the rest of the original RED remained unchanged. The other works on NLRED are [29], where the optimal 3-rd order polynomial packet dropping function for NLRED in the presence of self-similar traffic was presented, and [30], where the comparative analysis of NLRED with other queueing mechanisms was made.

In order to improve the bandwidth fairness of classic RED [3] in [31] the new AQM algorithm called Bandwidth-Fair RED (BF-RED) was proposed. This algorithm, according to the authors, guarantees the bandwidth fairness by controlling the throughput of high bandwidth flows to protect the rest of the traffics when the router tends to be congested. The main idea of BF-RED algorithm is to evaluate the bandwidth usage by monitoring the queue length and to increase the drop probability for the high bandwidth flows when the bandwidth of the router is not enough.

In [32] the new AQM algorithm, Hybrid Random Early Detection (HRED), combining the more effective elements of such algorithms as BLUE [33, 34] and the proportional controller [35] with RED core by extending RED with a second probability parameter to provide stability under steady load, was proposed. HRED maps instantaneous queue length to a drop probability, automatically adjusting the slope and intercept of the mapping function to account for changes in traffic load and to keep queue length within the desired operating range.

The modified version of Adaptive RED [25], named Refined Adaptive RED (Re-ARED), was introduced in [36]. This algorithm rearranges queue size near the specified target queue size.

The another version of Adaptive RED [25] was Stabilized ARED (SARED) algorithm, proposed in [37]. In this algorithm the Exponential Weighted Moving Average (EWMA) of the instantaneous queue size from ARED was modified by using two different queue weights in order to hold queue stable and closer to target area.

Pre-estimation RED (PERED) algorithm was proposed in [38] as a new adaptive RED algorithm, which adjusts the RED parameters based on the previous estimation to gain better performance. DiffServ PERED (version of RERED for Differentiated Service (DiffServ) network) adjust the parameters not only according to the estimation made by PERED, but also based on the priorities of service subscribers.

In [39] the Queue Variation Adaptive RED (QVARED) algorithm, based on the variation of a queue per hour in order to be responded to bursty traffic more actively, was presented. This algorithm enhanced link efficiency and dynamically dropped packets due to have high throughput in case of bursty traffic.

The novel server-based congestion control algorithm, called SF-RED [40], was designed to provide inter-server fairness service in a simple and scalable manner by using multiple virtual RED queues, which are differently parameterized and are maintained in a single physical FIFO (First In First Out) queue.

The robust two-timescale simultaneous perturbation stochastic approximation algorithm with deterministic perturbation sequences for optimization of RED parameters was proposed in [41] and named Optimized RED (O-RED).

4. 2007

Another modification of the ARED algorithm [25], depending on changing the maximum dropping probability p_{\max} by calculating the dropping probability at every arrival on the basis of a linear equation that reflects the slope of the drop probability – mean queue length and traffic load characteristics, was presented in [42]. The variation of the maximum probability in the proposed algorithm depends on the incoming arrival rate and the current average mean queue length. The

slope of the curve of the drop probability function is varied according to the variation of incoming arrival rate.

Adaptive Virtual Queue RED (AVQRED), described in [43, 44], was designed as modification of VQ-RED (VQRED) [45] for satellite networks. The AVQRED algorithm constructs a virtual queue and feeds the virtual queue sizes to the RED algorithm instead of feeding the weighted average queue sizes to it. AVQRED reshapes the incoming traffic according to the desired link utilization, so the RED parameters w_q and p_{\max} are no longer in the algorithm because their functionalities are replaced by the desired link utilization.

In order to provide QoS in a multi-rate WLAN, where the throughput of every wireless node should be independent of other nodes' transmission cost (defined as the channel usage time), the Temporal Fair RED (TFRED) algorithm was introduced in [46] to address the congestion, efficiency, and fairness problems in WLAN (wireless local area network) by setting different drop probabilities for each flow going through the access point.

Fuzzy control RED (FCRED or FconRED) algorithm [47] was developed to overcome the drawbacks of the original RED by using a fuzzy controller to adjust the maximum drop probability p_{\max} to stabilize the average queue length around the target queue length.

The new policy which favors packets with higher distance from source was introduced in [48] and named as Distance-Dependent RED (DDRED). The idea of DDRED is to eliminate packets having consumed fewer physical resources and thus coming from sources nearer to the congested router. By eliminating such packets, retransmission will be faster.

The new algorithm, Stochastic RED (StoRED), based on stochastic fair queuing and classic RED, was proposed in [49]. StoRED tries to enforce inter-flow fairness by distinguishing the active flows into a limited number of groups stochastically based on the bandwidth share obtained by flows. The algorithm tunes the packet dropping probability in such a way that the packets of the flow with higher transmission rate will more likely be dropped than flows with lower rate. For unresponsive flows (UDP flows) the modification of StoRED, named StoRED+, was given.

The modification of Adaptive RED (ARED) [25, 50], based on the multiplicative-increase multiplicative-decrease (MIMD) approach instead of additive-increase multiplicative-decrease (AIMD) policy and therefore named MIMD ARED, was described in [51].

In [52] the new RED algorithm named Preferential Dynamic Threshold RED (PDT-RED) and its optimized version OPDT-RED were proposed. These algorithms dynamically adjusted values of Q_{\min} and Q_{\max} thresholds by taking into account packets priority (all incoming packets are divided into several types with assigned priorities, packets with higher priority are dropped (marked) with a lower probability) and unused buffer space.

The idea of using neural networks for early congestion prediction (a prediction tool to determine the future values of the queue size (based on current and previous values of the queue length) and the necessity of packets to be dropped (marked) if the predicted queue size goes beyond the targeted value) is at the heart of the Neural Networks RED (NN-RED) algorithm [53].

The Dual RED algorithm for active congestion control specific for the handover traffic was proposed in [54]. The proposed mechanism is called Dual RED, because when the handover is finished the original RED (oRED) is used unchanged and an add-on RED (aRED) is only used temporarily during a handover to handle the handed-over traffic. The structure of Dual RED in some way is similar to RIO [55].

In [56] the novel method using stochastic learning automata and thus named Learning automata RED (LARED) was introduced. In LARED the RED thresholds Q_{\min} and Q_{\max} in order to guarantee the target value of the delay are dynamically adjusted.

In [57] the authors put forward a fuzzy self-tuning PD-RED algorithm that uses a fuzzy controller to regulate the Proportional Derivative (PD) controller's parameters in real-time, which allows to gain rapid response and keep the queue length within the target values.

5. 2008

The linear model of Gentle RED (GRED) [27], named GRED Linear, was presented in [58]. The discrete-time queuing model of GRED algorithm was constructed and analyzed the performance of a single queue node. It was proposed to decrease linearly the packet arrival probability value in order to control congestion. The comparison of GRED Linear with other versions of RED algorithm was conducted in [59].

The improved RED algorithm named Enhanced RED (ERED, EnRED) based on congestion detection and congestion avoidance was introduced in [60]. In order to adapt RED parameters to the dynamic changes of network in the practical application it was proposed to combine the current queue length Q and the average queue length \hat{Q} to a single parameter \tilde{Q} by using the weight w_q .

In [61] it was proposed to use a fuzzy logic (FL) controller technique based on the traditional RED algorithm to discover the congested router buffer as soon as the congestion occurs in the network. The new algorithm was named as Fuzzy-logic Controller-based RED (FConRED). This algorithm uses the average queue length and the packet loss rate as input linguistic variables and produces the packet dropping probability as a single output linguistic variable.

The new version of Modified RED (MRED) [62], named Progressive RED (PRED), was introduced in [63]. PRED not only adopts the instantaneous queue size to adjust the threshold Q_{\max} dynamically to make adaptive response toward the instantaneous network condition, but also regulates the packet dropping probability non-linearly and progressively to adapt to various network conditions by comparing the instantaneous queue size with the progressive maximum queue threshold parameters.

The Kohonen-RED (KRED) algorithm, based on Kohonen neural network model, was described in [64]. It was proposed to compute the value of p_{\max} parameter by using a Kohonen neural network.

In [65] two multiple RED routers algorithms of congestion control for two layers' network were suggested. The first algorithm — fair AQM algorithm, which extends the classic RED algorithm to edge routers and core routers, implements fair link capacities of edge routers. The second algorithm (more precisely, two versions of the algorithm) — unequal AQM algorithm tries to control the link capacities for the accessed edge routers and implements unequal link capacities of edge routers, but requires the core routers to have multi-queues buffers. Two versions of unequal AQM algorithm for the core router are considered: if the number of queues equals that of accessing edge routers and if the number of queues is far smaller than that of accessing edge routers.

In [66] the Autonomous RED (AURED) algorithm allowing a complete autonomous p_{\max} adjustment process by tuning the packet drop probability according to the performance variation between two consecutive sampling periods was proposed.

6. 2009

Two new version of classic RED — Barrier optimized RED (B-RED) and Penalty optimized RED (P-RED) were introduced in [67] as obtained by barrier (Barrier optimized RED) and the penalty (Penalty optimized RED) function approaches solutions to probabilistic constrained optimization problem by assuming a nonlinear relationship between the RED average queue length and its parameters as the variables of the optimization problem. The proof of convergence of proposed B-RED and P-RED algorithms to RED was given in [68].

In [69] the new active queue management algorithm, Effective RED (ERED), was presented. The aim of ERED was to reduce packet loss rates in a simple and scalable manner by changing Q_{\min} and Q_{\max} thresholds and by controlling instantaneous queue size Q together with average queue size \hat{Q} . Also it was proposed to control average queue size \hat{Q} when connections immediately reduce their sending rate in the case of no congestion. The performance evaluation and comparison of ERED with some other Active Queue Management algorithms was presented in [70].

The idea of using hazard rate function for estimation of RED packet drop probabilities was proposed in [71] and the new algorithm was named Hazard rate estimated RED (HERED). The usage of hazard rate function for a packet dropping function allows to make packet dropping gentler at light traffic load but more aggressive at heavy load.

The Priority Self-adaptive RED (PSRED) algorithm designed for Ad hoc networks with flows with different priorities was introduced in [72, 73]. The aim of the algorithm is to establish a balance between the queue length and the packet loss probability by self-adapting the values of p_{\max} .

The mechanism for RED parameters (thresholds Q_{\min} and Q_{\max} , maximum drop probability p_{\max} and queue weight w_q) simple, scalable and systematic tuning in response to changing network conditions (traffic load, link capacity and round-trip time), named as Auto-Parameterization RED (APRED), was proposed in [74]. This algorithm based on nonlinear dynamic model of TCP behavior which was developed by using fluid-flow and stochastic differential equation analysis.

The packet dropping algorithm, based on a self-tuning proportional and Integral feedback controller, which considers not only the average queue length at the current time point, but also

the past queue lengths during a round-trip time to smooth the impact caused by short-lived traffic dynamics, was introduced in [75] and named Self-tuning Proportional and Integral RED (SPI-RED).

The modified version of RED algorithm [3], called Multi RED (MRED), which was proposed in [76] as an effective way to reduce packet loss rates in the internet by computing the packet drop probability based on described heuristic method and enabling bandwidth allocation over a single link to different types of traffics.

The enhanced version of classic RED, named Light-weight Flow information RED (LwFRED), was designed in [77] for improving the fairness of RED aided by light-weight flow information. The basic idea of LwFRED was to classify flows into groups (like in [49] but in a different way) and adjust the dropping probability of each group according to its behavior.

The robust AQM algorithm for wireless Ad hoc networks was proposed in [78] and named Adhoc Hazard RED (AHRED). In order to prevent congestion which behaves rapidly according to the density of traffic load the described algorithm uses a packet drop probability function based on Weibull model of a hazard rate function (the conditional probability that a system will fail instantaneously some time after time t given that it has survived up to time t).

7. 2010

In [79] the new version of RED algorithm mechanism for congestion avoidance in wired networks based on a learning-automata-like (LAL) philosophy and therefore named learning-automata-like RED (LALRED) was introduced. The main aim of LALRED was to optimize the value of the average queue size used as a control parameter for congestion avoidance and to consequently reduce the total loss of packets at the queue. It was achieved by stationing a LAL algorithm at the gateways and by discretizing the drop probabilities. The application of LALRED for optical networks was presented in [80].

The Fuzzy Q-learning RED (FQL-RED) algorithm based on Adaptive RED (ARED) [25] and Fuzzy RED [81, 82] was proposed in [83]. This algorithm uses a Q-learning method enhanced with a fuzzy inference system in order to ensure RED with self-adaptation and improved performance.

In [84] the novel autonomous Proportional and Differential RED algorithm (NPD-RED) was proposed as an extension of RED for the TCP/RED dynamic time-delayed model in wired network and wired-wireless network routers. NPD-RED is based on a self-tuning feedback proportional and differential controller, which not only considers the instantaneous queue length at the current time point, but also takes into consideration the ratio of the current differential error signal to the buffer size. Also the new probability packet dropping function, based on changes in the instantaneous queue and the differential in queue length, is introduced.

The novel version of RIO-C (RED with In/Out and Couple queue) [85], named RIO Based On Priority and Fair (PFRIO), was presented in [86]. The main change was made in the calculation of average queue length in RIO-C algorithm to decrease the influence of the number of low drop-precedence packet on high drop precedence packet by introducing the new parameter, which makes the influence change dynamically in accordance to the number of packets.

In [87] the discrete-time dynamical model of TCP and UDP congestion control at the hosts coupled with RED active queue management at the routers, named TCP-UDP-RED, for controlling bifurcations and chaos in the internet congestion control system for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) network was proposed.

The Robust RED (RRED) algorithm to improve the TCP throughput against Low-rate Denial-of-Service (LDoS) attacks was presented in [88]. The basic idea behind the RRED was to detect and filter out attack packets (by using the proposed new detection algorithm) before a normal RED algorithm was applied to incoming flows.

The new active queue management algorithm for Assured Forwarding (AF) services guaranteeing minimum bandwidth provided based on RIO algorithm [55] and Weighted Fair Queuing (WFQ) was introduced in [89]. In the proposed scheme, the control functions for RIO and WFQ are enhanced under the assumption that they are used for input (RIO) and output (WFQ) queue management.

In [90] the novel algorithm called RIO based on Fractional Exponent Coupling (RIO-FEC), based on RIO-C ((RED with In/Out and Coupled queue)) and RIO-D (RED with In/Out and Decoupled queues) algorithms [85] was proposed. The novelty of RIO-FEC lies with the fact that a controllable scheme for determining the coupling level among virtual queues was introduced by expressing the coupling level as a polynomial function with a fractional exponent as the power of the polynomial.

8. 2011

The new modification of the ARED algorithm [25] was introduced in the [91] and named Self-tuning RED (St-RED). In the proposed algorithm the appropriate value of the parameter p_{\max} was dynamically obtained based on history information of both p_{\max} and the average queue size in a some period of time. Also the parameter w_q was properly chosen according to a linear stability condition of the average queue length.

The modified version of RIO-C [85] algorithm with only change in calculation of average queue length was proposed in [92] and named Weighted-queue-length RIO-C (WRIO). WRIO realizes relative discrimination of different drop precedence, and improves link utilization, especially for the networks with TCP traffics.

The improved RED algorithm with sinusoidal packet-marking probability and dynamic weight (SW-RED) was introduced in [93]. The proposed algorithm dynamically adjusts the average queue weight and packet drop probability, making it smaller when approaching to Q_{\min} , and greater when close to Q_{\max} .

Another version of the ARED algorithm [25], New Adaptive RED (NARED), was presented in [94]. In NARED the packet drop probability function is nonlinear smoothed by using the membership function of the ascend demi-cauchy of fuzzy distribution in order to make the speed of growth of packet loss rate relatively slow near Q_{\min} threshold and relatively faster near the Q_{\max} threshold. Also for adapting to the changes of network environment the parameter p_{\max} is dynamically adjusted by the length of average queue.

In [95] the new approach to modify ARED algorithm [25] in order to maintain the instantaneous queue length in the buffer and estimate the packet dropping probability was developed. The proposed algorithm named as Hazard rate based Heuristic ARED (HHA) because the original ARED packet drop function was extended by using the random probability Weibull distribution with a non-linear hazard rate (instantaneous failure rate) function.

In [96] the hop-to-hop controlled hierarchical multicast congestion control mechanism combining RED [3] (the ability to keep low delay while pursuit larger throughput, but also the strong sensitivity to parameters) and hop-to-hop (HTH) algorithm (the ability to rapidly respond to congestion and effectively improve throughput as well as utilization of link, but the need to use too much router resources in case of many streams) was introduced and analyzed.

The Weighted RED (WTRED) algorithm for congestion handling in TCP networks and increasing network performance by dynamically adjusting RED's maximum threshold, minimum threshold and weight parameters (based on the actual buffer size) was proposed in [97].

The novel adaptive version of Gentle RED (GRED) [27] was proposed in [98] and named Adaptive GRED (AGRED). Adaptive GRED detects congestion at router buffers in an preliminary stage, and enhances the parameters setting of the Q_{\max} threshold and the probability p_{\max} . The performance analysis of AGRED and comparison with RED [3] and (GRED) [27] was conducted in [99], the comparison with GRED-Linear [58] was made in [59].

In order to deal with RED such problems as sensitivity to traffic load and parameters configuration and the variety of the equilibrium queue length because of congestion degree and parameter settings the improved RED (named IRED) algorithm was presented in [100]. The proposed algorithm uses auto-tuning proportional integral (PI) probability as an adaptation mechanism designed to adjust the maximum packet drop probability p_{\max} for stable average queue length.

The modification of GRED [27] and NLRED [28] was proposed in [101] and named Modified RED (MRED). It is quite similar to GRED except that the linear packet dropping function was replaced by a nonlinear (quadratic) function as in NLRED algorithm.

9. 2012

The new per user AQM policy designed for blind network optimization, named the User Random Early Drop (URED) algorithm, which is a modification of the Flow RED (FRED) [102] and enforces fair resource allocation among users (tunnels), was introduced and evaluated in [103].

The Modified Random Early Detection (ModRED) algorithm was presented in [104]. It was proposed to restrict the TCP transmission window with the flow control window instead of the congestion control window, thus controlling the transmission window with a finer granularity.

For the purpose of countering slow start that causes rapid increase in load of the bottleneck router, the Harsh RED (HRED) algorithm was proposed in [105]. By taking advantage of well-defined TCP

slowstart behavior, the HRED queue average was made to cross HRED minimum threshold Q_{\min} on a timely manner in order to start “a count-down” for actual HRED dropping by setting the HRED parameters w_q and p_{\max} to a very large value compared with the recommended values for RED [3]. The evaluation and comparison of HRED with other AQM algorithms was conducted in [106].

The novel algorithm to achieve bandwidth fairness of RED with packet size consideration, named Bandwidth fair considering packet size RED (BF-PS-RED) as modification of BF-RED algorithm [31], was proposed in [107]. BF-PS-RED gathers packet size information (in order to the compensate unfairness resulted from the packet size difference) and uses it for adjusting the maximum drop probability p_{\max} of a high throughput flow together with drop-weight.

The modification of Refined Adaptive RED (Re-ARED) [36] algorithm, named Fast Adapting RED (FARED), was presented in [108]. This algorithm efficiently varies the maximum drop probability p_{\max} to improve the overall performance of the network/ FARED algorithm retains the target range as specified in Re-ARED algorithm [36] but modifies the upper bound and lower bound for parameters α and β respectively.

The modification of ARED [25] and Re-ARED [36] algorithms, named Cautious Adaptive Random Early Detection (CARED) algorithm that dynamically varies maximum drop probability p_{\max} either conservatively or aggressively based on the level of traffic load to improve the overall performance of the network, was proposed in [109]. The detailed study of the proposed CARED algorithm was carried out in [110].

10. 2013

The new version of RED algorithm, named Velocity RED (VRED) and based on using the queue length growth velocity in order to measure the congestion level in router, was introduced in [111]. VRED triggers the drop probability according to proposed metric. The usage of the queue length growth velocity, according to the authors, leads to fast reaction and hence improves the network performance because the packet dropping becomes gentler at light traffic load but more aggressive at heavy traffic.

In [112] the novel RED-based active queue management algorithm, called Full Information Feedback RED (FIF-RED). This algorithm for packet drop probability function not only considers the average queue length Q but also takes into account the growth rate of the instantaneous queue length.

The new version of RED algorithm, based on ideas of Robust RED [88] and designed to defend against DoS attacks by using the flows trust values for identification and dropping of malicious packets, was introduced in [113] and named as RED with Flow Trust (RED-FT).

The new AQM algorithm, with minimal changes to the classic RED algorithm, for providing the effective solution to avoid congestion collapse of network services by introducing new threshold U_{th} (Upper Threshold) and for better use of buffer space, was presented in [114] and named Upper threshold RED (URED).

The new modification of Gentle RED (GRED) [27] algorithm, designed for early stage congestion detection at the router buffer and named Dynamic Gentle Random Early Detection (DGRED), was introduced in [115]. The proposed DGRED algorithm depends on the stability of the average queue length at a specific level between Q_{\min} and dynamically changing Q_{\max} thresholds values. Also the dynamical threshold $2Q_{\max}$ is introduced. The simulation based performance evaluation of DGRED and comparison with several Active Queue Management algorithms for computer network was conducted in [116].

In [117] the packet correlated RED (PCRED) algorithm was proposed in order to forward the video packets in an efficient way by properly utilizing the unused bits of the differential service (DS) field of the IP header and providing some heuristic information for packet early discarding.

The version of RED algorithm with two nonlinear quadratic drop probability functions instead of a single linear function was introduced in [118].

The new robust RED algorithm, based on ideas of ARED [25], NLRED [28] and Re-ARED [36] algorithms and named Adaptive Nonlinear RED (ANLRED), was presented in [119]. This algorithm minimizes the parameter sensitivity of RED by making minimal algorithmic modifications without introducing some new parameters for better performance. ANLRED varies p_{\max} adaptively based on the change in average queue length \hat{Q} .

The new version of RED, named Modified RED (MDRED), was introduced in [120]. In the proposed algorithm the queue between minimum threshold Q_{\min} and maximum threshold Q_{\max} was virtually

divided into smaller subparts and calculation of packet drop probability was based on the average queue size \hat{Q} .

11. 2014

The extension of Gentle RED (GRED) algorithm [27], depending on a fuzzy logic system which reduces the large dependency on parameter settings, was proposed in [121] and named Fuzzy Logic Controller of Gentle Random Early Detection (GREDFL). The proposed algorithm uses the average queue length and the delay rate as input linguistic variables for a fuzzy logic system. The utilized fuzzy logic system produces a single output that represents a packet dropping probability, which in turn control and prevent congestion in early stage.

The new technique for network congestion avoidance and control, based on Balanced RED algorithm (BRED) [122, 123], was presented in [124] and named Neural Network Dynamic Balanced RED (NN-DBRED) because of using time delay line neural network as system's core to detect and separate adaptive and non-adaptive flows and also limit receive rate from them, to provide fairness between flows and avoid occurring congestion and buffer overflow.

The new enhanced algorithm, based on URED [114], was proposed in [125] to reduce parameter sensitivity and to improve the network performance in a congested networks by introducing a new threshold (the upper threshold) for better use of buffer space and to queue more packets which reduces packet drops. This algorithm was named Upper Threshold RED (UT-RED).

In [126] the Modified Gaussian Function based RED (MGF-RED) algorithm was introduced. The Modified Gaussian function was used for calculating the likelihood of packet drop as the average queue length increases the minimum threshold.

The new version of classic RED algorithm [3] with a modified weighted moving average used on a difference equation (a recursive equation) was proposed in [127]. It was shown that Depending on a particular optimality criterion, the proper values of the modified weighted moving average function can be chosen.

The modification of RED with new congestion metric (to forecast when the queue will be overloaded and to use for dynamically setting of RED parameters) based on the rate of which the queue is occupied, was considered in [128] and named QRTRED.

Two versions (Modified1 and Modified2) of Modified RED for stabilized queue (MRED-QS) were presented in [129]. In both versions the probability drop function was changed from linear to non-linear: logarithmic function for Modified1 version and exponential function for Modified2 version.

The new RED algorithm, named Random Early Dynamic Detection (REDD), was proposed in [130] in order to identify and control congestion and to enhance RED's performance in regards to mean queue length and packets waiting time. In the REDD the maximum threshold Q_{\max} position is adaptively changed depending of values of average queue length \hat{Q} . The comparison of REDD with Adaptive GRED (AGRED) [98] and GRED-Linear [58] was conducted in [59].

In order to provide better congestion control over the network while maintaining the advantage of RED the new algorithm called Enhanced Random Early Detection (ENRED) was proposed in [131]. The algorithm depends on enhancement of the average queue size on a way that limits queue size to minimize the delay and packet loss rate as compared to RED queue by introducing the new parameter — target queue (the difference between the current queue size and the average of the maximum threshold Q_{\max} and minimum threshold Q_{\min}).

In [132] the new RED-based AQM algorithm with modified probability drop function was presented, it was named Curvilinear Random Early Detection (CLRED). Instead of RED single linear function the two-segment (a quadratic and a linear) dropping function was proposed.

As the modification of the RIO-C algorithm [85] the Improved nonlinear RIO-C (INRIO-C) algorithm was proposed in [133]. This algorithm takes nonlinear characteristics between the average length of the queue and packets loss probability into consideration, and proposes piecewise smooth discarding functions. The algorithm adopts coupled approach to calculate the virtual queue, and sets priorities for different discarding threshold.

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The new version of RED with better fairness in dropping packets, promoting the real-time data transfers by considering the initial occupancy of queue and frame admission control based on this information, was considered in [134] and called fairRED.

The modified version of LALRED algorithm [79], based on the concept of a Learning Automata-Like (LAL) mechanism, was introduced in [135] and named Efficient LALRED (ELALRED). ELALRED algorithm was designed for congestion avoidance in wired networks by optimizing the value of the average queue size \bar{Q} .

The version of RED algorithm less biased against the User Datagram Protocol (UDP) packets was proposed in [136]. It was found out by authors that modification of the maximum threshold Q_{\max} and the final drop probability gives a considerable reduction in the UDP packet drop for a relatively lesser reduce in the TCP throughput.

The modified version of the Fair RED (FRED) algorithm [137], named Enhancement Fair RED (EFRED), was proposed in [138]. In EFRED the FRED probability drop function was modified and replaced by the hazard rate function.

The new version of RED with nonlinear cubic probability drop function was presented in [139] and named as Adaptive Sigmoid RED (ASRED).

The modified version of Cautious Adaptive RED (CARED) algorithm [109], designed for Heterogeneous network and based on fuzzy logic ideas, was developed in [140] and called as Fuzzy Cautious Adaptive RED (Fuzzy-CARED). In this algorithm the value of maximum drop probability p_{\max} is cautiously increased and decreased based on current traffic load after detecting congestion in the network.

13. 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 [141–149].

In the future, the authors plan not only to classify the considered algorithms based on the classification criteria presented in [141, 150, 151], but also to review and classify other active queue management algorithms.

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Хронология развития алгоритмов активного управления очередями семейства RED. Часть 2: 2006–2015

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Аннотация. Данная работа является второй частью большого библиографического обзора по алгоритмам семейства RED, представленных в научной печати с 1993 по 2023 год. В этой статье приведены данные по алгоритмам, опубликованным с 2006 по 2015 год.

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