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Chronology of the development of active queue management algorithms of RED family. Part 3: from 2016 up to 2024

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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 third part will provide data on algorithms published from 2016 to 2023.

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

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1. Introduction

This work is the third (the last) 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 previous parts were presented in [1, 2]

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 more then 240 algorithms.

The characteristics of the RED algorithm, as the reasons for its modifications were presented and described in [1, 2].

The review is structured as follows. 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 11 the authors discussed the results and the future research directions are highlighted.

2. 2016

The new AQM based congestion control mechanism for 4G/LTE networks with a minimal adjustment to classical RED algorithm [3] was proposed in [4] and named Smart RED (SmRED). In this algorithm in order to achieve the optimal end-to-end performance by regulating the queue size the packet drop probability function was divided into two sections for distinguishing of different network loads and dynamical adaptation to the levels of network load.

The novel version of RED, based on fuzzy logic, was introduced in [5] and named Fuzzy logic-based RED (FL-RED). In FL-RED the thresholds are dynamically increased or decreased according to fuzzy logic rules in order to utilize the resource effectively.

The combined modified version of NLRED [6] and REDwM [7] algorithms, Non-linear RED with Weighted Moving Average (NLREDwM) was proposed and analyzed in [8]. In this algorithm the average queue length was defined by the first order difference equation.

The new version of RED algorithm based on the optimized link state routing protocol (OLSR), named Optimized Link RED (OLRED), was described in [9]. OLRED algorithm selects optimal routing link periodically and calculates the average of queue size one time.

The version of Weighted RED (WRED) [10] with implementation of the optimized link state routing protocol (OLSR) was also presented in [9] and named as Optimized Link WRED (OLWRED). OLWRED algorithm selects optimal routing link and calculates the average of queue size periodically. Thus OLWRED is more sensitive to average queue size. The OLWRED algorithm was presented in more detail in [11].

The improved variant of RED algorithm to stability and thus named Stability RED (S-RED) was described in [12]. S-RED was focused on improving linear structure of packet drop probability function (the quadratic function was proposed) and reducing the quantity of setting parameters (the parameters $p_{\max}$ and $Q_{\max}$ were removed).

The modified version of Adaptive Gentle RED (AGRED) [13], designed for the detection of the congestion in early stage before the router buffer overflows and employing a dynamic setting of queue weight parameter w_q for the congestion control, was introduced in [14] and named Enhanced Adaptive GRED (EAGRED).

3. 2017

In order to guarantee the QoS requirements for real-time applications and to prevent starvation of the best effort traffic (TCP-based applications) in the presence of non-TCP-based applications (real-time traffics) the new modification of RED was introduced in [15] and named Dynamic Queue RED (DQRED). Incoming packets were classified by the DQRED algorithm into three class types, each of which was handled by one of three queues in the internet router. The queued packets were scheduled dynamically based on the number of active packets already existing in the queues during a predefined time interval.

In [16, 17] the Adaptive Queue Random Early Detection (AQMRD) algorithm was described. In this algorithm the information not just about the average queue size but also the rate of change of it was incorporated. Also the adaptively changing threshold level between $Q_{\min}$ and $Q_{\max}$ thresholds was introduced. For dynamic tuning of AQMRD algorithm parameters stochastic approximation based optimization scheme was proposed in [18].

The modified version of the Effective RED (ERED) [19] algorithm based on fuzzy logic (Fuzzy Inference Process) was introduced in [20] and named Fuzzy ERED (FERED).

The new version of RED algorithm with two virtual queues for TCP and UD traffic in order to minimize the packet loss of sensitive traffic flows was proposed in [21] and named MultiRED (MRED). The proposed algorithm takes into consideration the specific characteristics of the real-time traffic and provides a solution that keeps all the advantages of the existing active queue management QoS schemes and reduces as much as possible dropped packets due to buffer overflow.

The modified version of the Multi-level RED (MRED) [22] algorithm, highly depending on the weight w_q parameter and maximum drop probability $p_{\max}$, named Fair Weighted Multi-level RED (FWMRED), was described in [23].

The new RED algorithm with nonlinear probability drop function, based on the Hemi-rise cloud membership model, was proposed in [24] and named Cloud RED (CRED).

The extension of Smart RED algorithm [12] with probability drop function for different traffic-load scenarios was presented in [25] and called SmRED-i.

In [26] the Three-section RED (TRED) algorithm was proposed. The drop probability function in TRED is nonlinear and divided into three sections to distinguish between light, moderate, and high loads to achieve a tradeoff in the delay and the throughput between low and high traffic loads.

The new RED algorithm, which takes into account instantaneous and average queue sizes for the estimation of the queue occupancy, was described in [27] and named Adaptive Threshold RED (AT-RED).

4. 2018

The modified version of the Dynamic RED (DRED) algorithm [28] with fuzzy proportional integral derivative (FuzzyPID, FPID) controller, named DRED-FPID (Dynamic RED with Fuzzy Proportional Integral Derivative (FPID) controller) was proposed in [29] for congestion control by adjusting the transmission rate and packet loss probability calculation.

The modification of Adaptive Gentle RED (AGRED) [13] and Adaptive RED (ARED) [30] algorithms, was proposed in [31] and named Adaptive Gentle Adaptive RED (AGARED). The AGARED was aimed to provide better congestion control over the network taking advantages of AGRED and ARED algorithms by modifying the value of maximum drop probability $p_{\max}$ and enhancing the parameter setting of average queue size $\hat{Q}$.

In order to resolve this problem of parameter setting in Adaptive Queue Management with Random Dropping (AQMRD) algorithm [17] it was proposed in [18] to use the optimization technique based on stochastic approximation and thus the new version of the AQMRD was introduced — the Optimized AQMRD (OAQMRD) algorithm.

The new version of RED algorithm, based on Modified Gaussian Function based RED (MGF-RED) [32] and Modified RED (MDRED) [33] algorithms was introduced in [34] for tuning the values of RED thresholds $Q_{\min}$ and $Q_{\max}$ and packet drop probability and named as Hybrid Modified RED (HMDRED).

The modification of RED algorithm, based on monitoring of the average queue size $\hat{Q}$ for every single output queue, was named Probability based RED (P-RED) and introduced in [35] in order to enhance fairness by isolating ill-behaved flows and protecting the bursty and low speed flows in a larger amount.

The new version of Dynamic GRED (DGRED) algorithm [36], based on Markov-Modulated Bernoulli process (MMBP) and therefore named Markov-Modulated Bernoulli Dynamic GRED (MMBDGRED), was presented in [37]. The reason to use MMBP was to implement DGRED with multiple traffic classes with different priorities for each class and to enhance the mechanism of DGRED in stabilizing the average queue size $\hat{Q}$ between the given values of $Q_{\min}$ and $Q_{\max}$ thresholds (using variable calculating parameters stored in the MMBP states).

In [38] the new improved RED algorithm, named LTRED (L means the queue length and T means the thresholds), which incorporated the impact of load variation in early congestion notification along with tuning of threshold parameter of RED, was presented.

One more variant of RED algorithm using fuzzy logic to overcome problems of classical RED was proposed in [39] and called fuzzy logic RED (FLRED). Tn FLRED algorithm to predict and avoid congestion at an early stage the average queue size $\hat{Q}$ and the new parameter, delay D_{Spec}, were used.

In [40] the version of RED, where the packet drop probability function was divided into three sections (three dropping probabilities for different type of incoming traffic) with using Additive Increase Multiplicative Decrease (AIMD) technique, was introduced and named Modified RED (ModRED).

The new modification of RED, based on Q-learning algorithm for adjustment of the maximum drop probability $p_{\max}$ according to the network situation and named as Q-learning RED (QRED), was presented in [41].

The extended version of the Weighted RED (WRED) [10, 42] algorithm with the delay as one of the parameters of the algorithm (the estimation of which was based on the load factor) and with a type-2 fuzzy logic system, used to handle the nonlinear parameter uncertainties and to obtain more satisfactory results in terms of packet loss in the event of heavy congestion, was proposed in [43, 44].

The modification of DRED-FPID [29] with Deep Neural Network (DNN) was introduced in [45] and named as Dynamic RED with Fuzzy-Deep Neural Network Proportional Integral Derivative (DRED-FDNNPID). In DRED-FDNNPID the network traffic estimation was performed by using modified additive increase decrease scheme for congestion resolving.

For the congestion control in complex heterogeneous networks the version of Adaptive RED algorithm [30] with Bell type Fuzzy membership function (as the probability drop function) was proposed in [46] and named as BARED.

5. 2019

The modification of the RED [3] algorithm with a nonlinear probability drop function at the midpoint between the minimum $Q_{\min}$ and maximum $Q_{\max}$ thresholds was presented in [47] and named Half-Way RED (HRED).

The improved RED [3] algorithm for multimedia traffic was described in [48] by using reconfigurable approach to redefining the maximum drop probability $p_{\max}$ parameter by using the reconfiguration factor γ depending on current average queue size $\hat{Q}$, thresholds $Q_{\min}$ and $Q_{\max}$, target average queue size. The proposed algorithm was named as RED with Reconfigurable Maximum Dropping Probability (RRMDP).

The modified version of the Gentle RED algorithm [49] was proposed in [50] and named as Improved Gentle RED (IGRED). In IGRED the number of parameters used for definition of the probability drop function was reduced. The evaluation of the IGRED performance and comparison with other algorithms was conducted in [51].

The development of the Dynamic Gentle RED (DGRED) algorithm [36] with dynamic change of thresholds values in order to stabilize the average queue size, named as Stabilised Dynamic GRED (SDGRED), was presented in [52].

In [53] the Enhanced RED (EnRED) algorithm was presented. The current queue size q is used to determine the reaction scenario for packet dropping for each moment of a packet arrival, and the probability drop function was defined by the average queue size $\hat{Q}$.

Also in [53] the another version of RED algorithm, named as Time-Window Augmented RED (Windowed-RED), was described, where the average queue length on a limited time window $\hat{Q}_w$ was introduced instead of $\hat{Q}$ to determine the reaction scenario and to calculate drop probabilities.

The Novel RED algorithm was introduced in [54], where only the formula for the probability drop function was changed (the drop function remains linear, but when calculating the drop probability the threshold values $Q_{\min}$ and $Q_{\max}$ were squared, also the average queue size $\hat{Q}$ was squared).

The new congestion control mechanism for Constrained Application Protocol (CoAP) Observe Group Communication, based on the modification of the RED algorithm and a Fibonacci Pre-Increment Backoff (FPB) (to obtain retransmission timeout (RTO) estimations for the transmission of the CoAP messages) and named Congestion Control Random Early Detection (CoCo-RED), was proposed in [55].

In [56] the delay parameter was introduced to RED, so the proposed new algorithm was named Delay-Controller RED (DcRED). The delay parameter was calculated for each packet arrival, and the resulted value was used as a reference for the packet dropping. Because the delay conflicted with the throughput and the dropping rate, the balance between throughput and delay was maintained.

In order to reduce the packet loss and to improve the throughput the extension to the classic RED algorithm [3] was developed in [57] and named DyRED, The average queue size $\hat{Q}$ and the instance queue size q were used in DyRED as congestion indicators and the maximum threshold $Q_{\max}$ was dynamically changed to control the congestion in the router buffer at the early stage.

6. 2020

In [58], the RED-Exponential (RED_E) algorithm was introduced, and it was proposed to drop arriving packets in an exponential manner (the exponential form of the probability drop function) without utilizing the maximum packet dropping probability.

The new RED algorithm with current traffic load as a congestion indicator, was proposed [59] and named Flexible Random Early Detection (FXRED). In order to maintain stable performance FXRED tuned its drop probability suitable to the observed load situation (increasing if load becomes high in order to avoid overflow and congestion, decreasing as load becomes low in order to maximize link utilization and throughput).

In [60] the new congestion control method, named Double Index RED (DI-RED) and based on usage of a cache state with a dual threshold in the router buffer, for wireless sensor networks (WSNs) was introduced. In DI-RED a channel transmission state was implemented as a new indicator to control the packet drop probability, based on the control of the average queue size.

The three nonlinear modifications of the Gentle RED (GRED) algorithm [49] were presented in [61]. The first version was the nonlinear NLGRED_1 algorithm with fixed value of the $Q_{\max}$ threshold and variable value of the maximum drop probability $p_{\max}$. The second version was the nonlinear NLGRED_2 algorithm with variable value of the $Q_{\max}$ threshold and fixed value of the maximum drop probability $p_{\max}$. And the third modification was the Reconfigurable Nonlinear GRED (RNLGRED) algorithm, switching between the NLGRED_1 and NLGRED_2 algorithms.

The new version of the Adaptive RED (ARED) algorithm [30] with modified probability drop function (the nonlinear quadratic function instead of the linear) was described in [62] and named Quadratic Adaptive RED (QARED).

The Weight Queue Dynamic Active Queue Management algorithm (WQDAQM), based on the Stabilized Dynamic GRED (SDGRED) algorithm [52], was proposed in [63]. WQDAQM was designed to control and manage the packet drop probability by maintaining the queue weight w_q and the thresholds dynamically.

7. 2021

Based on the S-RED [12] the Quadratic Random Early Detection (QRED) algorithm was developed in [64] with a quadratic probability drop function (instead of linear one) and a new parameter, called target queue q_t for better use of buffer space. This parameter was defined as the difference between the current queue size and the average of $Q_{\min}$ and $Q_{\max}$ thresholds.

In [65] the Self-Adaptive RED (SARED) algorithm was proposed. In this modification of the Adaptive RED algorithm [30] not only average queue size $\hat{Q}$ was considered as a congestion indicator, but also the ratio of the total capacity demand of the current traffic to the available output (bottleneck) link's capacity (traffic load). In SARED, the maximum drop probability $p_{\max}$ was adapted based on an observed network's traffic load. Two different probability drop functions were introduced: linear for a high load in order to be aggressive for avoiding congestion and forced packet drops and nonlinear for low and moderate loads with increasing value of the degree of nonlinearity for decreasing load in order to be very gentle so as to avoid link under-utilization.

The Enhanced Congestion Control RED based mechanism (EnCoCo-RED) for CoAP observe group communication as modification of the CoCo-RED algorithm [55] was presented in [66]. The version of RED algorithm, which was used for CoCo-RED, was improved with dynamic buffer management in order to provide a selective backoff algorithm (SBA) and include a congestion measurement process.

The new version of the RED algorithm with dynamic tuning of RED parameters ($Q_{\min}$ and $Q_{\max}$ thresholds, the maximum drop probability $p_{\max}$), named Congestion Control Algorithm using Buffer Occupancy RED (CCA-BO-RED), was introduced in [67]. In the CCA-BO-RED algorithm the rate of occupancy of the queue, called Buffer Occupancy (BOC), was proposed as a new congestion parameter. This new parameter infers network conditions from the rapidity of the buffer occupancy in the router. Also it was proposed to use the additive-increase and multiplicative-decrease approach for the maximum drop probability $p_{\max}$ instead of multiplicative increase and decrease.

In [68] several modifications of the RED algorithm were described. The first model, called Application of Dynamic Weight with Distance to Improve the Performance of RED (ADWD-RED-IP), was based on dynamic setting queue parameters, especially weight parameter w_q. The second model was proposed for reducing the rate of packet loss by using both the average queue size and the current queue size as the arguments of the packet drop function and was named Active Queue Management in RED to Reduce Packet Loss (AQM-RED-RPL). The third model, the Predictable Active Queue Management to Reduce Sensitivity of RED Parameter (PAQM-RS-RED), was based on the Adaptive RED algorithm [69] with adaptation of the maximum drop probability $p_{\max}$ to retain the average queue size between $Q_{\min}$ and $Q_{\max}$ thresholds. The Revolutionary Active Queue Management Model Utilizing Queue Size Threshold Change (IAQM-TA-QZ) algorithm was presented as the fourth model with dynamic adaptation of $Q_{\min}$ and $Q_{\max}$ thresholds and drop probability to the load condition of traffic. In the fifth model, Nobel Congestion Control Algorithm Using Buffer Occupancy RED (CCA-BO-RED), the dynamic tuning of basic RED parameters based on the rate of occupancy of the queue, as a congestion parameter, was introduced as in [67]. Finally, in the sixth model, Active Queue Management in RED considering Critical Point on Target Queue (AQM-RED-CPTQ), the new parameter called the goal queue q_t, defined as in [64], was introduced. The first and the second models, Application of Dynamic Weight with Distance to Improve the Performance of RED (ADWD-RED-IP) and Active Queue Management in RED to Reduce Packet Loss (AQM-RED-RPL) were also described in [70].

The improved RED-based algorithm, named Quadratic-Linear RED (QLRED), was presented in [71]. In this algorithm the probability drop function was divided into two parts: the quadratic packet drop function in order to achieve a low packet dropping probability at low traffic loads and the linear packet drop function in order to achieve a high packet dropping probability at high traffic loads.

8. 2022

The new AQM algorithm, based on Gentle RED (GRED) [49], Adaptive Gentle RED (AGRED) [13], Effective RED (ERED) [19] and Enhanced Adaptive Gentle RED (Enhanced AGRED) [14] algorithms was considered in [72] and named as Changeable Dynamic Gentle RED (CDGRED). In order to stabilize the average queue size $\hat{q}$ the dynamic changing of two thresholds ($Q_{\max}$ and $2Q_{\max}$) out of three ($Q_{\min}$, $Q_{\max}$ and $2Q_{\max}$) was proposed. Also the comparison of the CDGRED performance with FLRED [39], DGRED [36] and Enhanced AGRED [14] algorithms was conducted.

The new version of classic RED algorithm [3] with two linear packet drop functions for light and heavy traffic loads instead of a single linear drop function in RED [3], named RED-Improved (RED-I), was proposed in [73].

The improved version of Adaptive RED (ARED) algorithm [30] for satellite networks with cubic drop function was presented in [74] and named Improved ARED (I-ARED).

The new AQM algorithm for improving the overall end-to-end delay, throughput, and packet delivery ratio of the massive NB-IoT 5G network while using UDP was introduced in [75] and called Aggressive RED (AgRED). In AgRED algorithm the sigmoid function was used for calculation of drop probabilities for the arriving packets in the initialization phase, with a higher probability of dropping broadcast packets.

In [76] the modification of the RED active queue management algorithm with mixed shape drop function (the linear drop function for low and moderate network traffic loads and the exponential function for computing the packet drop probabilities for high traffic loads) was proposed and named RED-linear exponential (RED-LE).

Another modification of the RED algorithm with combination of a nonlinear (the quadratic drop function to ensure a slow increase of the packet drop probability from 0 to $p_{\max}$ for smaller average queue size when congestion was not too serious) and a linear (to ensure a fast increase of the packet drop probability from $p_{\max}$ to 1 for larger average queue size when congestion was very serious) packet dropping functions was introduced in [77] and named Improved RED (I-RED).

The new version of the RED algorithm with the ascending ridge function as a part of the probability drop function was proposed in [78] and named RED with the ascending ridge function (ARRED). The thresholds $Q_{\min}$ and $Q_{\max}$ were used as parameters of the ascending ridge function.

The novel modification of the RED algorithm, based on fuzzy logic similar to the FCRED (FconRED) [79], GREDFL [80], FERED [20] and FLRED [39] algorithms, and thus named the Fuzzy Comprehensive RED (FCRED), was described in [81] in order to deal with the gap in network monitoring and congestion control at the router buffer by using fuzzy inference process for management of three introduced indicators (average-based queue-related, arrival-related and departure-related) and the drop probability calculation.

The robust version of the RED algorithm, based on ideas from [82, 83], was presented in [84, 85] and called Beta RED (BetaRED) because of using the normalized incomplete beta function as a nonlinear packet drop probability function with dependence on two new parameters μ and σ (the mean and the standard deviation of the beta distribution). The basic idea of BetaRED was to maintain the average queue size $\hat{Q}$ close to a predetermined target queue size q_t and between $Q_{\min}$ and $Q_{\max}$ thresholds. So, the parameter μ was defined as the function of q_t, $Q_{\min}$ and $Q_{\max}$.

Also in [84, 85] two dynamical versions of the BetaRED algorithm were proposed. The first version, Adaptive Beta RED (ABetaRED) algorithm, was based on ideas of the Adaptive RED (ARED) algorithm [30] with the tuning of the thresholds parameters. In the second version, Dynamic Beta RED (DBetaRED) algorithm, the dynamic parameter (virtual target queue length) was introduced to correct deviations between the average queue size $\hat{Q}$ and the actual value of the target queue size q_t.

The Integrated RED (IRED) algorithm was presented in [86] with two new congestion indicators — the integrated arrival factor (based on queue length (current queue combined with a predetermined threshold value divided by the buffer's total capacity) and arrival rate (a weighted average of the current arrival value and the previous arrival value) and the integrated departure factor (based on departure rate and the queue length).

The novel version of the RED algorithm, called Improved RED (IM-RED), with combination of a nonlinear (the quadratic) drop function to deal with light and moderate network traffic loads and a linear drop function for heavy traffic load was introduced in [87]. The proposed drop functions are similar to functions, presented in [77]. The performance evaluation and comparison of IM-RED and IGRED [50] algorithms was conducted in [51].

Similar to I-RED [77] and IM-RED [87] algorithms in [88] the idea of quadratic (for a light or a moderate traffic load) and linear (for a heavy traffic load) probability drop functions was presented, so the new algorithm was named as RED-Quadratic Linear (RED-QL). But unlike the mentioned algorithms, in RED-QL an additional threshold value lying between the minimum Q_{min} and maximum Q_{max} thresholds was introduced.

In [89] the modification of Adaptive RED (ARED) [30] and Gentle RED (GRED) [49] algorithms with Markov decision process for adaptation of the queue weight values was presented and named as Markov decision process RED (MDPRED).

In the Linear RED (LRED) algorithm [90] it was proposed to use the adaptive estimated average queue length (the function of the differences in the estimated queue length and the actual queue length) as the congestion indicator and to simplify the calculation of the probability drop function as a linear function of the estimated queue length.

Based on ideas from [16–18, 91, 92] the novel network congestion control algorithm, called the Average Queue Length and Change Rate RED (AC-RED) was introduced in [93] with the average queue length change rate as a new parameter, reflecting the change of network traffic. The proposed AC-RED algorithm was compared with RED [3], ARED [30], URED [94], TRED [26] and AQMRD [17] algorithms.

In [95] the new version of the RED algorithm, the Double Linear RED (DL-RED) was presented with a packet drop function, consisting of two different linear functions (one for light and moderate loads, another for a heavy load).

9. 2023

The modification of the RED algorithm with two nonlinear probability drop functions (the quadratic function for light and moderate traffic loads, the exponential function for a heavy traffic load) was presented in [96] and named as Quadratic Exponential RED (QERED) algorithm. Also the new threshold Q_{target} was introduced ($Q_{\text{min}} < Q_{\text{target}} < Q_{\text{max}}$).

In [97] the Modified Dropping RED (MD-RED) algorithm was proposed. In this algorithm the single linear probability drop function from RED was replaced by two drop functions: the linear for low and moderate traffic loads and the exponential for a high traffic load. Also as in [96], the new threshold Q_{target} was introduced ($Q_{\text{min}} < Q_{\text{target}} < Q_{\text{max}}$).

The modification of the RED algorithm with the exponential probability drop function was considered in [98] with the nonlinearity parameter γ for the adjustment of the bending degree of the exponential function.

In [99] the novel fuzzy-based AQM algorithm based on a computationally efficient precise fuzzy modeling with the Genetic Algorithm (FREDGA) was proposed in order to achieve a balanced and equitable distribution of the resources and avoid bandwidth wasting resulting from unnecessary packet dropping.

The improved version of active queue management algorithm ARED [30] the Switchable ARED (SARED) was introduced in [100] to guarantee the comprehensive QoS performance of a low earth orbit (LEO) satellite network by dynamically updating of RED parameters through the link load information and the predicting the network state of satellite nodes based on obtained link information. The SARED algorithm uses both an S-shaped probability drop function together with a linear function in order to obtain a better stability for the queue size.

The novel version of the classic RED algorithm [3] for the a-priori congestion detection was presented in [101]. The Decision Tree-aided Random Early Detection (DREaD) algorithm proposes to use the machine learning technique (Decision Tree classifier) at the router in order to predict congestion by observing the behavior of the queue at the router (based on the queue characteristics).

10. 2024

Two nonlinear modifications of RED algorithm was presented in [102]: Amended RED (AmRED) and RED-Quadratic Exponential (RED-QE). In AmRED the RED queue threshold range is divided into three sections and three dropping functions (quadratic, linear and exponential) are used. In RED-QE algorithm the RED queue threshold is divided into two sections and two drop functions (quadratic and exponential) are used.

In [103] the Classified Enhanced Random Early Detection (CERED) algorithm for real-time packets and non-real-time packets in Wireless Sensor Networks (WSNs) was proposed. In CERED, the preemption priority was conferred on real-time packets, and the queue management with enhanced initial drop probability $P_{\min>0}$ was implemented only for non-real-time packets. Also in [103] the preemptive priority M/M/1/C vacation queuing model with queue management was presented.

The novel version of RED algorithm — the Amended Dropping Random Early Detection (AD-RED) with two nonlinear packet dropping functions (quadratic plus exponential) as for RED-QE algorithm in [102] was presented in [104].

The Random Early Detection algorithm with static priority scheduling and controlled delay (RED-SP-CoDel) algorithm was introduced in [105]. In this algorithm the RED AQM component was added to the combination of the Controlled Delay (CoDel) [106] AQM mechanism with Static Priority (SP) scheduling for QoS differentiation.

11. Conclusion

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 [107–115].

In the future, the authors plan not only to classify the considered algorithms based on the classification criteria presented in [107, 116, 117], but also to review and classify other active queue management algorithms.

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Хронология развития алгоритмов активного управления очередями семейства RED. Часть 3: 2016–2024

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Аннотация. Работа является третьей частью большого библиографического обзора по алгоритмам семейства RED, представленных в научной печати с 1993 по 2023 год. В данной части будут приведены сведения по алгоритмам, опубликованным с 2016 по 2023 год.

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