RANKING OF ROUTER-BASED CONGESTION CONTROL APPROACHES FOR HIGH SPEED NETWORKS USING AHP

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Abstract

Congestion control is a critical issue in internet environment because of its complex characteristics. Network congestion control can be characterized by several criteria like causes of congestion, type of congestion symptoms, congestion control location and objectives while congestion control. Thus, network congestion control can be treated as multi criteria decision-making problem. Analytical hierarchy process (AHP) is one of the ways to solve the multi criteria decision-making problem. In this paper, an attempt has been made to compute ranking of router-based congestion control approaches for high speed network using AHP model. The computed ranking will help to propose a decision-making model for router based congestion control algorithm and facilitate to select appropriate congestion control approach for a particular network environment.

Keywords**:** congestion control; Active Queue Management; high speed network; analytical hierarchy process; AHP; multi criteria decision-making; MCDM.

1. Introduction

The Router-based congestion control algorithms also known as active queue management (AQM) approach, for high speed networks have their own performance issues, different from traditional non-high speed networks. A network with a large bandwidth-delay product is commonly known as a high speed network or long fat network. Emergence of high speed networks motivated the research community to design a new class of router-based congestion control algorithms which can perform efficiently in such networks. As a result there are number of algorithms are proposed by the researchers and academicians. These algorithms are evaluated based on various performance issues like goodput, packet loss, fairness, link utilization, stability and complexity etc. These router-based congestion control algorithms may have focus on different performance criteria for different network environments. The main motivation behind this work is the fact that it is difficult to choose which algorithm will be appropriate for which network environment because every network environment may have their own specific performance requirements. Thus, selection of an optimal congestion control approach can be considered as a critical decision-making problem.

Therefore, the main emphasis of this work is to consider congestion control as a multi criteria decision-making (MCDM) problem and find an optimal solution by using a popular modelling technique known as analytical hierarchy process (AHP). This model is an attempt to provide a relative ranking of various AQM approaches, which can facilitate the researchers to select an optimal solution having highest ranking.

There are number of experimental evaluations have been performed by the researchers/academicians for the router based congestion control approaches in high speed networks [Padmavathi et al., 2010][Chrost et al., 2009] [Bitorika et al., 2004].These evaluations only give an idea about whether a particular algorithm is performing better for a specific performance criteria or not. Further, the experimental evaluation approach is unable to provide us the information regarding the relative ranking of various approaches. This work presents a qualitative analysis of router-based congestion control approaches by using a two phase AHP modelling. The idea is to provide a ranking for congestion control approaches, which will help to find the relative effectiveness of a particular approach against congestion control.

The paper is organized as follows: in Section 2, a brief review of previous experimental evaluations of router based congestion control approaches, conducted on high speed internet, has been mentioned. Section 3 explains how congestion control can be treated as a MCDM problem. Section 4 presents a brief discussion of AHP modelling technique used for solving MCDM problems. In Section 5, we explain an AHP model for router based congestion control approach in high speed network and discuss the major findings of this work. Finally, Section 6 concludes the paper.

2. Related Work

In literature, the problem of congestion has been studied widely in the context of high speed networks. Substantial protocol evaluation works have been reported regarding router-based congestion control approaches in high speed networks. All these evaluations are done by using simulation and experimentation on real test beds. Some significant experimental evaluations related to the topic are as follows:

Padmavathi et al.[Padmavathi et al., 2010] have performed a theoretical review of various router based congestion control approaches. They discussed AQM algorithms based on various congestion-metrics and classified them based on certain factors. This helps in identifying the AQM algorithms that regulate the congestion more effectively. Bitorika et al.[Bitorika et al., 2004] have performed a simulation based evaluation and comparison of a subset of AQM schemes. They used a specially designed framework which builds on the NS2 simulator for evaluation. The evaluation methodology adopted by them enables the direct comparison of AQM schemes, clearly highlighting their similarities and differences. Chatranon et al. [Chatranon et al., 2004] presented a survey to exhibit the state-of-the-art in router-based AQM mechanisms used to address the TCP-friendliness problem. They first described the most important issues to design AQM algorithms and then described the some important algorithms and compared them against these issues. In their work a qualitative comparison is included to compare all the existing schemes. Then, a quantitative performance evaluation is included to show the advantages and disadvantages of only those schemes that don't require full per-flow state information since they are more likely to be implemented in practice. Chrost et al. [Chrost et al., 2009] proposed a common testbed for the evaluation of active queue management mechanisms. It includes a specification of the network topology, link bandwidths and delays, traffic patterns on the application level, transport protocols, congestion level, bidirectional traffic characterization, metrics for the performance evaluation etc. The testbed presented by them is based on the newest TCP evaluation suite, properly tailored for the active queue management evaluation purposes.

AHP has been widely used in computer network area. Xi et al. [Xi et al., 2009] have proposed an AHP model to assess the computer network information security. They researched all kinds of factors of influencing network security and constructed the evaluation indexes for computer network information security. Misbah-Uddin et al. [Misbah-Uddin et al., 2009] have proposed an on-demand source routing protocol for MANET that works with six important QoS attributes by varying priority for different category of traffic flow by incorporating analytic hierarchy process (AHP) in their proposal. Awajan et al. [Awajan et al., 2008] proposed an enhanced source-based QoS routing algorithm that aims at reducing the complexity of route selection for services with multi QoS metrics. In their algorithm, they used AHP to find the best path between the service provider and the client that meets a list of constraints stored in a QoS profile. Alkahtani et al. [Alkahtani et al., 2006] have used the concept of AHP to propose anew algorithm called enhanced best effort quality of service routing (QoS) with multiple prioritised metrics for connection-oriented point-to-point communications. Fei and Xu [Fei and Xu , 2010] have used fuzzy AHP to construct a model of computer network security assessment in the light of the characteristics of computer network and the factors influencing the network security. They commented that the fuzzy AHP is an exploratory method for network security assessment. Kamiyama and Satoh [Kamiyama and Satoh ,2008] have considered network topology evaluation as a MCDM problem as it seriously affects network's cost, reliability, throughput, and traffic pattern. They clarified that AHP enables to choose desirable topologies according to the relative importance of each criterion. Kamiyama [Kamiyama , 2012] has found that network topology and data centre location strongly affect various evaluation criteria, such as cost, path length, and reliability; therefore, these criteria with different respective units need to be considered simultaneously when designing a data centre network. He proposed a design of data centre networks by evaluating both network topology and data centre locations simultaneously by using AHP.

Wang et al. [Wang et al., 2012] have proposed an AHP in load balancing is to minimize the demanded radio resources of the maximum load cell. Their main objective is to avoid the network congestion in the LTE networks with the multicast and unicast mixed services. They proposed system model of the demanded radio resources in the maximum load cell based on AHP. The proposed AHP in load balancing achieves less demanded radio resources of the maximum load cell than SFN mode for all the multicast services. Gamukama et al. [Gamukama et al., 2014] have presented a model based on AHP theory that lays strategies through which informed decisions for aligning stakeholders' goals can be made to use the internet as medium for enhancing national development initiatives. AHP-based model for structuring the problem is presented whose implementation lead in establishing utilities levels through that internet providers would adhere to in providing services to end users that also maximizes their utilities. Gamukama et al. [Gamukama et al., 2015] have proposed the mathematical foundations of a four level hierarchical model based on the AHP theory whose objective is to enable the computation of a priority vector for internet traffic classes in the context of development. Katsaros et al. [Katsaros et al., 2015] have performed a comprehensive study of the performance of routing protocols in distributed vehicular networks and proposed a novel and efficient routing protocol, namely cross-layer, weighted, position-based routing (CLWPR). Further, they used an AHP approach to combine multiple decision criteria into a single weighting function and to perform a comparative evaluation of the effects of aforementioned criteria on forwarding decisions. Kushwaha et al. [Kushwaha et al., 2016] have made an attempt to compute ranking of source-based congestion control approaches for high speed network using AHP model. They proposed a decision-making model for source based congestion control algorithm with an aim to facilitate the selection of appropriate source based congestion control approach for a particular network environment.

The above contributions demonstrate that although various attempts to evaluate the performance of router based congestion control approaches are available in the literature but a ranking of these approaches, considering it as a MCDM problem, by using AHP modelling for high speed networks has not yet been found. As mentioned earlier, there are various AHP models available in computer network area but very few are specific to congestion control problem. This work extends the above contributions further by suggesting a two-phase AHP modelling approach to evaluate the performance of router-based congestion approaches in High speed networks.

In this paper, we have proposed AHP model for router-based congestion control approaches specifically used in high speed wired networks. Congestion control is a global issue and requires equal attention for other types of network such as wireless networks, wireless sensor networks, mobile ad-hoc networks, etc. The AHP decision-making model can be applicable for these congestion control approaches.

3. Congestion control as a MCDM problem

Congestion control is a challenging issue in global internet because of its complex characteristics. Network congestion control can be characterized by several criteria like causes of congestion, type of congestion symptoms, congestion control location and objectives while congestion control. Kushwaha et al. explained how congestion control can be treated as a MCDM problem [Kushwaha et al., 2016].A brief discussion of network congestion characteristics is mentioned below:

3.1. *Cause*

There are several factors which are responsible for having congestion in a computer network. For example: spurious retransmissions, undelivered packets, fragment mismatch, large amount of control traffic, stale or unwanted packets and speed mismatch because of network heterogeneity etc.

3.2. *Symptom*

There are two main symptoms of congestion in the internet; first one is *packet loss* due to buffer overflow at router which leads to the packet retransmission. The second symptom is *increased delay* due to queuing in router buffers. However, packet loss is not a sufficient indication of congestion, in its own for wireless network. As wireless link suffer from high error and packet loss rates, it is required to differentiate between congestion loss and error loss.

3.3. *Control location*

Although congestion cannot be curbed permanently (since it is determined by the traffic patterns and not by the traffic-routing mechanisms), its adverse effects can be minimized by decreasing the packet drops in the network [Misra et al., 2010]. As network is considered as a distributed system, any problem arises in such a system requires a distributed solution. Thus, for congestion control in the network we need to apply the control at different locations in the internet. Thus, we need some control at 'end hosts' transmitting and receiving data. Such control is implemented by TCP at Transport layer. It is also required to impose some control at the intermediate nodes in between the transmission; such control is implemented by 'Router' by using AQM strategies at network layer. One more control offered by end host is using some flow control methods implemented at data link layer.

3.4. *Objectives*

The major concern of a congestion control approach is to handle the congestion event effectively. Effectiveness of a particular approach relies on the several objectives which must be met by the data communication network while congestion control. In literature large number of design goals for congestion control has been taken into consideration such as goodput, packet loss, fairness, link utilization, stability and complexity. These objectives have been considered as the major performance parameters while experimental evaluation of congestion control approaches. Each parameter takes different values depending upon the architectural behavior and testing environment of the data communication network under consideration. Architectural behavior of a data communication network can be specified by several factors as:

• type of network: wired, wireless, mobile ad-hoc, wireless sensor
• topology: dumb-bell, parking-lot, complex parking-lot, etc.
• traffic description:
  a. number of flows
  b. nature of flow: long-term, short-term, delay sensitive, having same RTT or different.
  c. existence of background traffic
  d. existence of reverse path traffic
  e. size of router buffer at bottleneck: either equal to bandwidth-delay product or less than that
• bottleneck link bandwidth: traditional low speed or high speed
• End host TCP discipline: Scalable TCP, CUBIC TCP, Hamilton TCP etc.

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Due to complexity of communication network, it is difficult to achieve all these goals simultaneously by a single congestion control approach.

3.5. *Trade-offs*

In addition to that one more obstacle against meeting the design goals of congestion control approach is the existence of trade-off between various objectives. Following trade-offs have been observed in literature, among the design objectives of congestion control approaches: goodput and queuing delay trade-off, link utilization and queue length trade-off, link utilization and queuing delay trade-off, goodput and queue length trade-off [Kushwaha and Gupta, 2014].

From the above discussion it can be inferred that there are several factors responsible for effective congestion control. Thus, while selecting a best congestion control algorithm; one has to consider the effectiveness of that algorithm with respect to various criteria under observation. Thus, selection of a congestion control approach for a particular environment can be considered as a MCDM problem. There are several models have been proposed for solving a MCDM problem, these are AHP, elimination and choice translating reality (ELECTRE) and the Technique for Order Preference by Similarly to Ideal Solution (TOPSIS), fuzzy AHP, etc. In this paper, we have used AHP model for ranking router-based congestion control algorithms which we found more suitable for our problem.

4. Analytical hierarchy process [Harker et al., 1987; Saaty, 1980]

The AHP is a comprehensive framework designed to cope with the intuitive, the rational, and the irrational when decision makers make multi-objective, multi-criterion and multi-factor decisions with or without certainty about any number of alternatives [Harker et al., 1987]. The AHP approach was designed to help decision makers incorporate qualitative (intangible) and quantitative (tangible) aspects of a complex problem. It systematically solves complex problems by decomposing the structure of a problem into hierarchies and the users then make pair wise comparison judgements as to importance or preference to develop priorities in each hierarchy. After Thomas Saaty first introduced AHP in 1976 [Saaty, 1980], the concept has gradually evolved through a number of applications as diverse as energy allocation, marketing decisions, project selection and evaluation, technology selection, new product screening, and conflict resolution. In general, there are four basic steps in using AHP [Andijani, 1998; Douligeris and Pereira, 1994; Alkahtani et al. 2006]:

I. The description of a complex decision problem as a hierarchy.
At the top of the hierarchy or the first level is the main objective of the problem. To help ease the decision process, the problem is broken down into all possible related criteria contributing to the decision process. These form the second level of the hierarchy. The problem may even be further refined into sub-criteria under each of the selection criteria in level two. The decision maker is responsible for the size and complexity of the hierarchy with both left to his own discretion. At the lowest level of the hierarchy are the decision alternatives.

II. The use of pair-wise comparisons to estimate the relative weight (importance or priority) of the various elements to each other. This gives what is called the priority weights.
The next step is for the decision maker to create square pair-wise comparison matrices of the selection criteria, sub-criteria and decision alternatives. From these pair-wise comparison matrices, the decision maker will be able to derive the weights of the criteria, sub-criteria and decision alternatives that lead to the overall best decision. The AHP is also suitable for qualitative problems where Saaty's scale of relative importance is used in order to make the judgments in the pair-wise comparison process.

III. The use of pair-wise comparisons to estimate the relative weight (importance) of the various elements on each level of the hierarchy. This gives what is called the score of each level in each element.
Saaty suggested the eigenvector method (EM), where the right principal eigenvectors of the pair-wise comparison matrices are used as the derived priority vectors. For example, consider pair-wise comparisons of decision alternatives under criterion 1. A rough estimate of the eigenvector can be obtained as follows. First all elements in a column are divided by that column's sum producing a new normalized matrix. Next, the values of all elements in each row of the new normalized matrix are added up and then divide the sum by the number of elements in the row. The results would be the weights of the decision alternatives under selection criterion 1. Priority vectors are similarly derived for all the other pair-wise comparison matrices.

IV. The integration of these weights, from 2 and 3, to develop an overall score of decision alternatives.
The last step of synthesizing results throughout the hierarchy is to compute the overall ranking or weights of decision alternatives using the standard AHP weighting and adding process. The decision maker thus obtains the best decision for his/her problem: the alternative having the largest synthesized final priority.

5. The AHP model for network congestion control algorithms

In this section, an attempt has been made to compute the ranking of router based congestion control algorithms with AHP. Router based congestion control is implemented at network layer using AQM. Router based approaches are further categorized as: Heuristic approach, Optimization approach and Control-theoretic approach. There are number of algorithms has been proposed under each category. Thus it is difficult to predict which approach is most effective for network congestion control for a specific scenario.

We have used the similar two layered approach for AHP modeling of router based approach. First we compute individual ranking of router based congestion control approaches in each category i.e. Heuristic approach, Optimization approach and Control-theoretic approach and then finally compute the ranking among these three categories.
The overall decision making process is divided into two phases.

- **Phase 1:** (Intra Approach Modeling)
  In first phase three AHP models have been developed for each approaches Heuristic approach, Optimization approach and Control-theoretic approach. These models help us to find the best alternative under their respective categories.
- **Phase 2:** (Inter Approach Modeling)
  In this phase a single AHP model has been proposed by using the results of first phase modeling. This model finds the best alternative among all the categories.

5.1. *Identification of the Criteria for Evaluation*

The effectiveness of a particular router based congestion control approach depends upon the values of various performance metrics like goodput, packet loss, fairness, link utilization, stability and complexity. A router based congestion control approach having an optimal value for all these parameters simultaneously can be considered as a best approach. Thus the performance metrics goodput, packet loss, fairness, link utilization, stability and complexity are considered as major criteria for the evaluation of router based congestion control approaches in both the phases of AHP modeling. A brief overview of each criterion under consideration is as follows:

a. Goodput

Goodput is defined as the number of bits per unit of time forwarded to the correct destination, minus any bits lost or retransmitted [Newman, 1999].

b. Packet loss

Packet loss can occur en route; this can impact the end-to-end performance measured at the receiver end. The packet loss ratio can be assessed by simply evaluating the loss ratio as a function of the number of lost packets and the total number of packets sent.

c. Fairness

The criteria 'fairness' was considered by various researchers for the evaluation of end to end approaches. The main goal of fairness is to share the network resource in a fair manner.

d. Link Utilization

Link utilization is defined as the fraction of link capacity being used for transferring data. Utilization can be expressed as a decimal point between 0 and 1 or as a percentage (%).Utilization is calculated by the formula
*Link Utilization= total throughput*100/(bottleneck-link bandwidth* bottleneck-link delay)*

e. Stability

The safety of an AQM scheme is directly related to its stability under varying operating conditions such as varying traffic profiles and fluctuating network conditions. Since operating conditions can vary often, the AQM needs to remain stable under these conditions without the need for additional external tuning. Network devices can experience varying operating conditions depending on factors such as time of the day, deployment scenario, etc. For example:

- Traffic and congestion levels are higher during peak hours than off-peak hours.
- The capacity available can vary over time
- The ability of an AQM scheme to maintain its control over the queuing delay and buffer occupancy can be challenged.

f. Complexity

Complexity refers to implementation complexity of particular AQM.

5.2. *Alternative Selection*

There are numbers of alternatives available for router based congestion control algorithms under each category of approaches: Heuristic, Optimization and Control-theoretic. We have selected some anchor algorithms under each category for our discussion. We have taken a different approach for alternative selection.

5.3. *Phase 1 Modeling: AHP model for Intra Protocol Evaluation*

In this phase, for each category of approaches i.e. Heuristic, Optimization and Control-theoretic, a separate AHP model has been designed. These models help us to find the best alternative under their respective categories. Description of each AHP model for phase 1 modeling has been drawn as follows:

Step 1: Alternative Selection

I. Heuristic based AQM selection

There are number of algorithms have been proposed by the researchers/academicians under heuristic based congestion control approaches. In this study only four alternatives are selected as anchor algorithms for heuristic based approaches as: RED [Floyd et al.,1993], CHOKe [Pan et al., 2000], SFB [Feng et al., 2001] and Yellow [Long et al., 2005]. The reason behind this selection is that these are the algorithms which have been considered by most of the research community for the experimental evaluation as observed from the literature. The level 1 AHP model for heuristic based AQM is shown in Fig. 1.

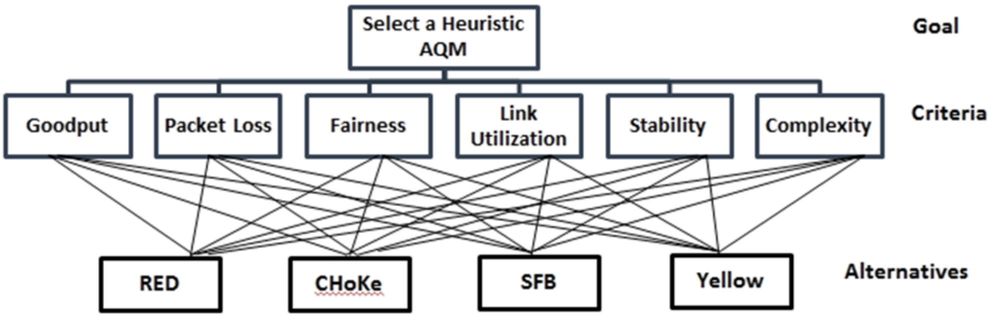

Fig.1. Level 1 AHP for Heuristic based AQM

II. Optimization based AQM selection

On the other hand very few algorithms have been proposed under optimization based approach of router based congestion control. Here the two alternatives are selected as: REM [Lapsley et al., 1999], AVQ [Kunniyur et al., 2001]. Out of these two REM is the first and one of the representative algorithm proposed for router based congestion control under optimization based category. The level 1 AHP model for optimization based AQM is drawn in Fig. 2.

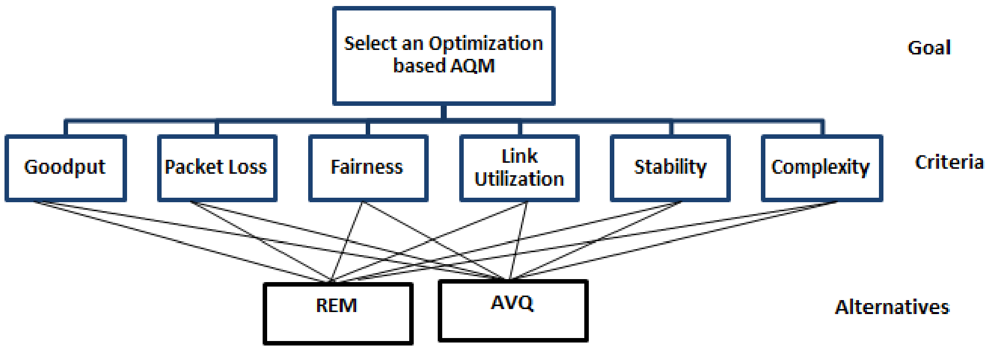

Fig.2. Level 1 AHP for Optimization based AQM

III. Control-theoretic AQM selection

There are various algorithms have been proposed under control-theoretic router based congestion control approaches. In this modeling only two alternatives are selected for control-theoretic approaches as: LRED [Wang et al., 2005] and PI [Hollot et al., 2002]. The level 1 AHP model for control-theoretic AQM is discussed below in Fig. 3.

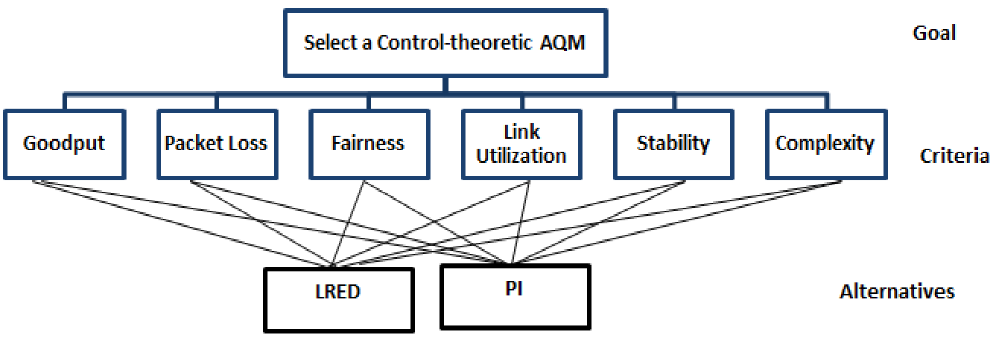

Fig. 3. Level 1 AHP for Control-theoretic AQM

Performance Parameters	***Goodput***	***Packet loss***	***Fairness***	***Link Utilization***	***Queue Stability***	***Complexity***
RED	y	y	y	y		
REM	y	y	y			
Choke	y		y			
DRED		y		y		
AVQ	y	y		y	y	y
SFB	y	y	y			
PI				y	y	
CARE	y	y	y		y	y
FABA	y		y			y
Yellow		y		y	y	
E-RED	y				y	
RAQM	y	y		y	y	y
DC-AQM		y		y	y	
Q-SAPI		y		y		
LRED	y		y		y	y
PAQM		y		y		y
IMC-PID		y		y	y	
AOPC		y		y	y	
Effective-RED	y	y				
P-AQM	y	y	y	y	y	
HSTCP-H2	y	y	y		y	y
RC		y			y	
Weight	**13**	**17**	**9**	**12**	**13**	**7**
Relative weight	**0.20**	**0.27**	**0.14**	**0.19**	**0.20**	**0.11**

Step 2: Relative weight computation of different criteria

Weights are assigned to different criteria based on their relative importance. A study of twenty two AQM algorithms has been performed (Table 1) to find the fact how many performance parameters are considered, by the researchers, for the evaluation of their algorithms out of the six performance parameters: goodput, packet loss, fairness, link utilization, stability and complexity.

Table 1 list various router based congestion control approaches and their respective performance parameters taken into consideration which is denoted by the letter 'y' in their respective cells. This table also exhibits the relative weight calculation of various criteria under consideration. Relative weight of a particular criterion is calculated by dividing its individual weights to the total weight.

The relative weights of different criteria for selection of router based congestion control algorithm have been computed and displayed in table 2.

Table 2. Computed Relative weights of different criteria for AQM

Criteria	**Rank**
Goodput	0.20
Packet loss	0.27
Fairness	0.14
Link Utilization	0.19
Stability	0.20
Complexity	0.11

Step 3: Decision weights calculation

We have adapted a scaling method based on performance parameter analysis as used in AHP modeling of source based approaches. Table 3 exhibits a performance parameter analysis of source based congestion control approaches, which is obtained based on our previous studies and reviews [Padmavathi et al., 2010][Chrost et al., 2009] [Bitorika et al., 2004][Wang et al., 2005][Wang et al., 2008] of router based congestion control approaches.

Table 3. Performance parameter analysis of router based congestion control approaches

Router Based Congestion Control Approaches		Performance Metrics					
		Goodput	**Packet Loss**	**Fairness**	**Link Utilization**	**Stability**	**Complexity**
Heuristic	**RED**	*slightly better*	*slightly better*	*slightly better*	*Good*	*Better*	*slightly better*
	Choke	*Better*	*better*	*better*	*Better*	*Better*	*Better*
	SFB	*Better*	*better*	*better*	*Good*	*Better*	*slightly better*
	Yellow	*slightly better*	*best*	*slightly better*	*Best*	*Good*	*slightly better*
Optimization	**REM**	*Poor*	*good*	*better*	*Good*	*Poor*	*slightly better*
	AVQ	*Good*	*good*	*slightly better*	*Best*	*Better*	*slightly better*
Control-theoretic	**LRED**	*slightly better*	*better*	*slightly better*	*Good*	*Good*	*slightly better*
	PI	*Good*	*good*	*better*	*Good*	*slightly better*	*Better*

The proposed scaling of criteria is shown in table 4.

Table 4. The Proposed Scaling Criteria

AHP Scale of Importance for pairwise comparison	Numeric Rating
Poor	**1**
Slightly Better	**2**
Better	**3**
Good	**4**
Best	**5**

Based on the scaling mentioned in table 4, a pair wise comparison for selected performance parameters, under each category: heuristic, optimization and control-theoretic, is displayed in the form of matrix.

The matrices of pair wise comparison of the heuristic based AQM alternatives with respect to each criterion and their local priorities are given in table 5. It contains a set of six sub tables; containing pair wise comparison of heuristic based TCP alternatives with respect to six different criteria: goodput, packet loss, fairness, link utilization, stability and complexity. Last column in each sub table shows the relative rank of each heuristic based AQM with respect to the criteria listed in the top left corner of respective sub table.

Table 5. Comparison Matrices for Heuristic based AQM

Goodput	RED	Choke	SFB	Yellow	W_i
RED	1.00	0.67	0.67	1.00	**0.20**
Choke	1.50	1.00	1.00	1.50	**0.30**
SFB	1.50	1.00	1.00	1.50	**0.30**
Yellow	1.00	0.67	0.67	1.00	**0.20**

(a)

Packet Loss	RED	Choke	SFB	Yellow	W_i
RED	1.00	0.67	0.67	0.40	**0.15**
Choke	1.50	1.00	1.00	0.60	**0.23**
SFB	1.50	1.00	1.00	0.60	**0.23**
Yellow	2.50	1.67	1.67	1.00	**0.38**

(b)

Fairness	RED	Choke	SFB	Yellow	W_i
RED	1.00	0.67	0.67	1.00	**0.20**
Choke	1.50	1.00	1.00	1.50	**0.30**
SFB	1.50	1.00	1.00	1.50	**0.30**
Yellow	1.00	0.67	0.67	1.00	**0.20**

(c)

Link Utilization	RED	Choke	SFB	Yellow	W_i
RED	1.00	1.33	1.00	0.80	**0.25**
Choke	0.75	1.00	0.75	0.60	**0.19**
SFB	1.00	1.33	1.00	0.80	**0.25**
Yellow	1.25	1.67	1.25	1.00	**0.31**

(d)

Stability	RED	Choke	SFB	Yellow	W_i
RED	1.00	1.00	1.00	0.75	**0.24**
Choke	1.00	1.00	1.00	0.75	**0.24**
SFB	1.00	1.00	1.00	0.75	**0.24**
Yellow	1.00	1.33	1.33	1.00	**0.29**

(e)

Complexity	RED	Choke	SFB	Yellow	W_i
RED	1.00	0.67	1.00	1.00	**0.22**
Choke	1.50	1.00	1.50	1.50	**0.33**
SFB	1.00	0.67	1.00	1.00	**0.22**
Yellow	1.00	0.67	1.00	1.00	**0.22**

(f)

It can be inferred from table 5 that, Choke and SFB both perform equally better with respect to goodput and fairness. Yellow performs best in terms of packet loss, link utilization and stability.

The matrices of pair wise comparison of optimization based AQM alternatives with respect to each criterion and their local priorities are given in table 6.

Table 6. Comparison Matrices for Optimization based AQM

Goodput	REM	AVQ	W_i
REM	1.00	0.25	**0.2**
AVQ	4.00	1.00	**0.8**

(a)

Packet Loss	REM	AVQ	W_i
REM	1.00	1.00	**0.5**
AVQ	1.00	1.00	**0.5**

(b)

Fairness	REM	AVQ	W_i
REM	1.00	1.50	**0.60**
AVQ	0.67	1.00	**0.40**

(c)

Link Utilization	REM	AVQ	W_i
REM	1.00	0.80	**0.44**
AVQ	1.25	1.00	**0.56**

(d)

Stability	REM	AVQ	W_i
REM	1.00	0.33	**0.25**
AVQ	3.00	1.00	**0.75**

(e)

Complexity	REM	AVQ	W_i
REM	1.00	1.00	**0.50**
AVQ	1.00	1.00	**0.50**

(f)

Table 6 contains a set of six sub tables; containing pair wise comparison of optimization based AQM alternatives with respect to six different criteria: goodput, packet loss, fairness, link utilization, stability and complexity. Last column in each sub table shows the relative rank of each optimization based AQM with respect to the criteria listed in the top left corner of respective sub table. It can be inferred from table 6 that, AVQ performs better than FAST TCP with respect to link utilization, goodput and stability. On the other hand both are equally good packet loss and complexity.

The matrices of pair wise comparison of the control-theoretic AQM alternatives with respect to each criterion and their local priorities are given in table 7.

Table 7. Comparison Matrices for Control-theoretic based AQM

(a)

Goodput	LRED	PI	W_i
LRED	1.00	0.50	**0.33**
PI	2.00	1.00	**0.67**

(b)

Packet Loss	LRED	PI	W_i
LRED	1.00	0.75	**0.43**
PI	1.33	1.00	**0.57**

(c)

Fairness	LRED	PI	W_i
LRED	1.00	0.67	**0.40**
PI	1.50	1.00	**0.60**

(d)

Link Utilization	LRED	PI	W_i
LRED	1.00	1.00	**0.50**
PI	1.00	1.00	**0.50**

(e)

Stability	LRED	PI	W_i
LRED	1.00	2.00	**0.67**
PI	0.50	1.00	**0.33**

(f)

Complexity	LRED	PI	W_i
LRED	1.00	0.67	**0.40**
PI	1.50	1.00	**0.60**

Table 7 contains a set of six sub tables; containing pair wise comparison of control-theoretic based AQM alternatives with respect to six different criteria: goodput, packet loss, fairness, link utilization, stability and complexity. Last column in each sub table shows the relative rank of each control-theoretic AQM with respect to the criteria listed in the top left corner of respective sub table. It can be inferred from table 7 that, both alternatives: LRED and PI performs equally better with respect to link utilization. On the other hand PI is better than LRED with respect to all other parameters except stability.

The next step is to establish the composite or global priorities of the various heuristic based, optimization based and control-theoretic AQM's. We lay out the local priorities the heuristic based, optimization based and control-theoretic AQMs with respect to each criterion in a matrix and multiply each column of vectors by the priority of the corresponding criterion and add across each row which results in the desired vector of the heuristic based, optimization based and control-theoretic AQM respectively.

Table 8 lists the global ranking of each heuristic based AQM.

Table 8. Local and Global Priorities: Heuristic based AQM

AQM	Goodput (0.20)	Packet Loss (0.27)	Fairness (0.14)	Link Utilization (0.19)	Stability (0.20)	Complexity (0.11)	Global priority
RED	0.20	0.15	0.20	0.25	0.24	0.22	**0.2282**
Choke	0.30	0.23	0.30	0.19	0.24	0.33	**0.2845**
SFB	0.30	0.23	0.30	0.25	0.24	0.22	**0.2838**
Yellow	0.20	0.38	0.20	0.31	0.29	0.22	**0.3117**

It can be inferred from Table 8 that Yellow having highest ranking, is the best alternative under heuristic based category. CHoke and SFB both having nearly same global ranking, are the second best alternatives under the same category. The alternative RED has the lowest global rank.

Table 9 lists the global ranking of each optimization based AQM. It can be inferred from Table 9 that AVQ having highest ranking, is the best alternative under optimization based category. Because of poor goodput and stability REM is the second best alternatives under the same category.

Table 9. Local and Global Priorities: Optimization based AQM

AQM	Goodput (0.20)	Packet Loss (0.27)	Fairness (0.14)	Link Utilization (0.19)	Stability (0.20)	Complexity (0.11)	Global priority
REM	0.2	0.5	0.60	0.44	0.25	0.5	**0.4476**
AVQ	0.8	0.5	0.40	0.56	0.75	0.5	**0.6624**

Table 10 lists the global ranking of each Control-theoretic AQM. It can be inferred from Table 10 that PI having highest ranking, is the best alternative under Control-theoretic category. Because of poor goodput and high complexity LRED is the second best alternatives under the control-theoretic category.

Table 10. Local and Global Priorities: Control-theoretic AQM

AQM	Goodput (0.20)	Packet Loss (0.27)	Fairness (0.14)	Link Utilization (0.19)	Stability (0.20)	Complexity (0.11)	Global priority
LRED	0.33	0.43	0.40	0.5	0.67	0.40	**0.5111**
PI	0.67	0.57	0.60	0.5	0.33	0.60	**0.5989**

Thus it can be concluded from table 8, table 9 and table 10 that Yellow, AVQ, PI are the better alternative under heuristic based, optimization based and control-theoretic category of router based congestion control algorithms respectively.

5.4. *Phase II Modeling: AHP model for Inter Protocol Evaluation*

The first phase modeling gives us an idea about the best alternatives of router based congestion control algorithms under each category. It can be observed from the table 8, table 9 & table 10 that **Yellow AQM**, is the best alternative for heuristic based, **AVQ AQM** is the best alternative for optimization based and **PI AQM** is the best alternative for control-theoretic category respectively.

The another useful idea may be to compute the ranking among these three approaches, i.e. Heuristic based, Optimization based, Control-theoretic, to get to know which one is preferably better than another. For this purpose, information generated from the first phase can be utilized and a new AHP model for ranking among three approaches can be drawn. This is the motto for phase II modeling. The criteria ranking and criteria scaling used in phase 1 modeling can be utilized in this phase.

A new AHP model is drawn as depicted in fig. 4, which has goal to select the best approach among the Heuristic based, Optimization based and Control-theoretic approach.

The criteria used for the modeling is same as described in phase 1. The three alternatives used in this phase are the three best anchor algorithms found under each category in phase 1 modeling i.e. Yellow for heuristic based, AVQ for optimization based and PI for control-theoretic.

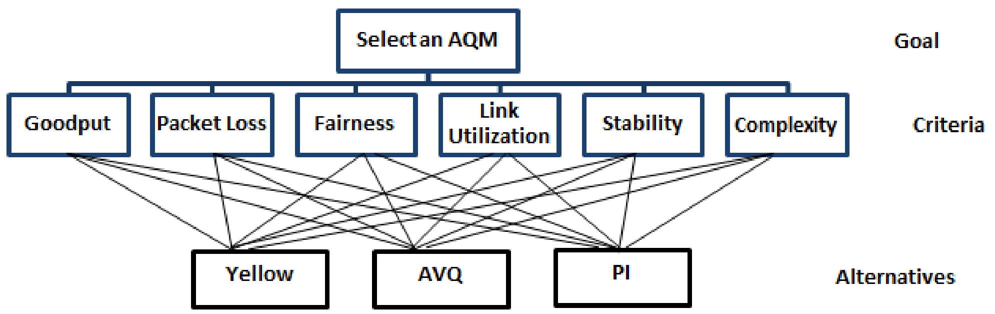

Fig. 4. Level 2 AHP model for selecting Router based Congestion control approach

Based on the criteria ranking and criteria scaling used in phase 1 modeling, the matrices of pair wise comparison of the three best alternatives: Yellow, AVQ, PI, with respect to each criterion and their local priorities are given in table 11.

Table 11 contains a set of six sub tables; containing pair wise comparison of three best alternatives with respect to five different criteria: goodput, packet loss, fairness, link utilization, stability and complexity. Last column in each sub table shows the relative rank of each AQM with respect to the criteria listed in the top left corner of respective sub table.

It can be inferred from table 11 that, Sync TCP perform best with respect to RTT fairness, friendliness, efficiency and convergence.

Table 11. Comparison Matrices and local priorities for AQM

Goodput	Yellow	AVQ	PI	W_i
Yellow	1.00	0.50	0.50	**0.20**
AVQ	2.00	1.00	1.00	**0.40**
PI	2.00	1.00	1.00	**0.40**

(a)

Packet Loss	Yellow	AVQ	PI	W_i
Yellow	1.00	1.25	1.25	**0.38**
AVQ	0.80	1.00	1.00	**0.31**
PI	0.80	1.00	1.00	**0.31**

(b)

Fairness	Yellow	AVQ	PI	W_i
Yellow	1.00	1.00	0.67	**0.29**
AVQ	1.00	1.00	0.67	**0.29**
PI	1.50	1.50	1.00	**0.43**

(c)

Link Utilization	Yellow	AVQ	PI	W_i
Yellow	1.00	1.00	1.25	**0.36**
AVQ	1.00	1.00	1.25	**0.36**
PI	0.80	0.80	1.00	**0.29**

(d)

Stability	Yellow	AVQ	PI	W_i
Yellow	1.00	1.33	2.00	**0.44**
AVQ	0.75	1.00	1.50	**0.33**
PI	0.50	0.67	1.00	**0.22**

(e)

Complexity	Yellow	AVQ	PI	W_i
Yellow	1.00	1.00	0.67	**0.29**
AVQ	1.00	1.00	0.67	**0.29**
PI	1.5	1.5	1	**0.43**

(f)

The next step is to establish the composite or global priorities of the best alternative under heuristic based, optimization based and control-theoretic AQMs. We lay out the local priorities of the best alternative under heuristic based, optimization based and control-theoretic AQMs with respect to each criterion in a matrix and multiply each column of vectors by the priority of the corresponding criterion and add across each row which results in the desired vector of the heuristic based, optimization based and control-theoretic AQM respectively.

Table 12 lists the global ranking of each best AQM under the three categories. It can be inferred from Table 12 that Yellow AQM having highest ranking, is the best alternative as a whole. AVQ AQM is the second best alternatives. The alternative PI has the lowest global rank.

Table 12. Local and Global Priorities: AQMs

AQM	**Goodput** (0.20)	**Packet Loss** (0.27)	**Fairness** (0.14)	**Link Utilization** (0.19)	**Stability** (0.20)	**Complexity** (0.11)	**Global priority**
Yellow	0.20	0.38	0.29	0.36	0.44	0.29	**0.3715**
AVQ	0.40	0.31	0.29	0.36	0.33	0.29	**0.3706**
PI	0.40	0.31	0.43	0.29	0.22	0.43	**0.3703**

From table 12 it can be inferred that Heuristic based AQM (Yellow) is the best alternative among the three categories of algorithms for congestion control in high speed networks. Optimization based AQM (AVQ) is slightly better than Control-theoretic based AQM (PI). Thus by using Yellow AQM as a router based congestion control algorithm in a network, one can not only control the congestion, achieve an optimal balance between the various performance goals while congestion control.

We have considered limited number of algorithms that's why we observed minor difference among the ranking of router based approaches. If we include more number of algorithms for our study more generalized result can be obtained.

6. Conclusion

In this work, congestion control is considered as a MCDM problem. There are several models are available for solving a MCDM problem. In this paper, AHP model is used for modelling the selection of router based congestion control. Here a two phase approach is followed for modelling. The first phase modelling gives an idea about the best congestion control approach in each three categories: heuristic-based, optimization-based and control-theoretic of router-based congestion control algorithms for high speed network. Further, the second phase modelling gives the best alternative among the three categories: heuristic-based, optimization-based and control-theoretic by using the results of first phase.

As from the above discussion it is clear that because of MCDM nature of congestion control problem, there is a need of some model for proper selection of an optimal approach for congestion control in high speed network. The two phase modeling proposed in this work is an attempt to facilitate the research community in finding the relative ranking of considered approaches in both the phases. By using these ranking we can take the decision about the selection of an optimal approach for better router based control of congestion in high speed network. Congestion control is also considered as an optimisation problem as we have to achieve several conflicting goals while congestion control. Achieving higher goodput, minimal packet loss, higher link utilization, stability and complexity simultaneously is one of the conflicting goals while congestion control. Thus, selection of an router based approach which performs optimally for every performance criteria is a difficult issue, and the model presented in this work will try to give an optimal solution of this issue.

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